Aalto-yliopisto
School of Engineering

Lawangeen Bacha

Applications of steel fiber reinforced concrete in Finnish infrastructure

Master's thesis, submitted to conform to the requirements of the Building Technology degree.

Espoo 28 May 2019

Supervisor: Professor of Practice Jouni Punkki
Advisor: Lic.Tech. Mika Tulimaa

Author: Lawangeen Bacha

Title of thesis: Applications of steel fiber reinforced concrete in Finnish infrastructure

Master programme: Building Technology	**Code** ENG27
Thesis supervisor: Professor of practice. Jouni Punkki	
Thesis advisor(s): Lic. Tech. Mika Tulimaa	
Date 27.05.2019 **Number of pages** 1-131	**Language** English.

Abstract

Fibers are used widely in concrete industry now-a-days for a variety of purposes. Besides other fiber materials, Steel Fiber has much more significance due to its greater strengths and strain hardening behaviour. Steel fiber reinforced concrete (SFRC) reduces the cost while adding mechanical strengths to concrete. Such type of concrete uses readily available concrete materials for the mix except some special types of steel fibers.

This research focuses the structural/infrastructural use of steel fibers in concrete using materials available in Finland e.g cement, sand, and aggregates etc. The main focus rests on replacing conventional reinforcement with steel fibers. Different dosages of steel fibers are tested, in increasing order, to check the increasing strengths and ductility.

Thesis required beam and slab tests. Beam tests are performed according to SFS-EN 14651 and the slab tests are conducted as five-point bending test. The slabs with only steel fibers and with conventional reinforcements, both, are tested and compared.

Residual flexure tensile strength values against crack mouth opening displacements (CMODs) change with differential steel fiber dosage and concrete strength class. Such values cannot be extracted through interpolation and need tests to be performed. The values, as a results of beam tests, can be used for design purposes according to BY-66.

Moment capacities of the test slabs were derived forehand using the residual strengths of the used SFRC dosages. Design process is included in the appendix.

Keywords: Steel Fiber Reinforced Concrete [SFRC], Fresh properties, Compressive strength, Flexural strength, moment capacity, crack resistance, application of SFRC.

Acknowledgments

This research work ended with fruitful results. All the work was done at Aalto University. The versatile and heavily equipped laboratories at Aalto University enabled this research.

I express my sincere gratitude and respect to Prof. of practice Mr. Jouni Punkki, to have faith in me and supervising my research. His keen and precise directions enabled me to perform optimistically. Besides, thanks to staff scientist Fahim Al-Neshawy, laboratory technicians Mr. Pertti Alho and Mr. Janne Hostikka and especially laboratory manager Jukka Piironen who helped a lot in testing phase.

Rudus Oy funded this project and I would like to share my sincere gratitude to Mr. Mika Tulimaa for the trust and assistance through rough and tough. I would also like to thank Väyla, especially Mr. Jani Meriläinen, for partially funding this thesis and keenly observing my achievements. Lastly, I would like to thank Mr. Janne Heikkilä and Bermanto for providing fibers and valuable assistance. I hope my work adds some value to the target goal.

Finally, I would like to thank my family, friends and loved ones who have been true source of motivation. Their support and faith is appreciated.

I would like to dedicate this thesis to my grandfather Jamil Bacha who is my sole motivation and I give him all the credit for my successes, if I have any. He is no more with me but his presence will always be felt and his cheering on my every accomplishment will always be missed.

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List of Abbrevations

SFRC	*Steel fiber reinforced concrete*
a/d	*Aspect ratio : length / thickness*
CMOD	*Crack mouth opening displacement*
CTOD	*Crack tip opening displacement*
PC	*Plain concrete*
SFRS	*Steel fiber reinforced shotcrete*
PPFRC	*Plypropylene fiber reinforced concrete*
PYFRC	*Polyester reinforced fiber reinforced concrete*
SP	*Super plastisizers*
SCM	*Supplementary cementing material*
CRS	*Conventionally reinforced concrete*
F_x	*F= Force*
	x= CMOD
$f_{R.1}$	*Residual flexural tensile strength at CMOD = 0.5mm*
$f_{R.3}$	*Residual flexural tensile strength at CMOD = 2.5mm*
δ	*Deflection*
h_{sp}	*Depth of beam specimen*

CHAPTER 1 : INTRODUCTION

1.1 Background

Concrete containing hydraulic cement, water, coarse and fine aggregates, and discontinuous discrete fibers is called fiber-reinforced concrete. Addition of fibers can be of many types, of which steel fibers are generally used for structural purposes and synthetic fibers for delaying early cracking.

Concrete is the second most abundantly and widely used material for construction purposes. Its use is diverse and significant due to its special properties. Applications of concrete are wide and extensive. Approximately all the structure built nowadays use concrete, some way or the other. The flexibility of concrete plays an important role in its significance as concrete can be combined with a variety of composites used in the construction industry. Currently, concrete is widely used in the construction of highways, small scale and high-rise buildings, dams, retaining wall, pedestrian walkaways, bridges and much more. Concrete covers almost every aspect of construction and its properties can be altered in accordance with the requirements of the targeted structure.

The induction of fibers into binding material is an ancient process. Fibers, e.g. straws, horse hairs, and plant fibers, were introduced to concrete in its earlier age. The application of different fibers were considered effective and long lasting. A pueblo house in USA, built around 1540, is still in the standing position and is considered to be the oldest house constructed using fiber reinforced binding material. Initially, fibers were introduced to bricks as there were no bonding material present.

Fiber reinforcement concept was developed in modern times and asbestos fibers were introduced in early 20th century through Hatschek technology for making plates for roofing and pipes [*Andrej M. Brandt 2008].* In the modern era, research enabled to conclude much more positive aspects of fibers if added to concrete. A wide range of engineering materials are made up of such concrete composite mix which results in enhanced mechanical strengths and durability.

Wide range of fibers are present in the market currently, depending upon their own particular strengths and properties e.g. steel, glass, plastic, organic and in-organic etc. The basic fiber categories are steel, glass, natural and synthetic fiber materials. Fibers can be combined in such a way that each of the fiber type has its specific function – for example, short fibers eliminate shrinkage cracks and longer fibers have a structural function.

Fibrous concrete needs adequate design guidelines to be used for practical purposes. In a report ACI 544.1R-96, it states that SFRC has the tendency to work along the conventional reinforcement to add extra strength that might be compressional, flexural, tensile, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance.

Among the use of other fibers in concrete industry, steel fibers are used in abundance and excess. Many sizes and shapes are present in market related to steel fibers. Some common types of steel fibers used are straight slit, deformed slit sheet, crimped-end wire, and flattened-end slit sheet.

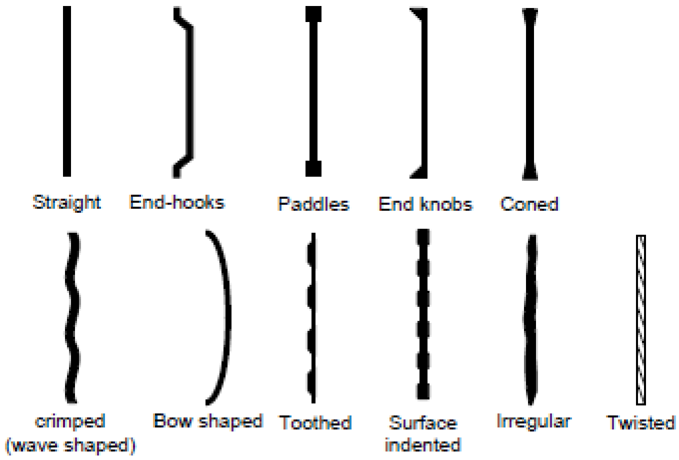

Figure 1: Common types of steel fibers [*Löfren 2005*]

Steel fibers vary depending upon the properties required. Aspect ratio [a/d] plays a vital role as many properties are directly linked to it. *ACI 544-1R* states that SFRC in its freshly mixed state are influenced by the aspect ratio of steel fibers, fiber geometry, volume fraction, the matrix proportions, and the fiber-matrix interfacial bond characteristics [*Löfren 2005*].

1.2 Research significance

The aim of this research project is to introduce SFRC to structural use. After thoroughly studying the major properties of SFRC, suggesting some structural use is addressed. The research encourages to use the local raw material available in Finland to derive a cost-effective and efficient SFRC mix.

It is believed that SFRC has much more tendency of adding value to construction industry. *ACI 318-11 commentary R11-4.6[f]* includes provisions for the use of fiber as a minimum shear reinforcement. Shear capacity of SFRC is 2.4-6 times higher than ordinary concrete which fulfill the code´s provision to be used as shear reinforcement.

The percentage use of fibers remained a hot topic as the properties of SFRC changes with the change in dosage. This research finds out a suitable percentage by volume of concrete to attain the desired properties and behavior.

1.3 Methodology

The methodology followed is mentioned as following;

- Extensive review of literature about SFRC and their applications.
- Selection of most potential applications for SFRC in Finnish infrastructure.
- Defining the required properties for the selected SFRC.
- Selection of suitable material for the mix that is available locally.
- Adjusting the workability of mix against steel fiber dosages.
- Performing mechanical and rheological tests of beams and slabs.
- Analyzing and concluding the results based on the above mentioned procedure.

1.4 Scope of the work

The work plan is summarized as following:

1.4.1 Preliminary laboratory tests

Following are the test performed prior to final tests:

- Adjusting workability of mix for every steel fiber dose.
- Slump tests
- Compressive cube tests

1.4.2 Final laboratory tests

Following are the tests performed on optimized mixes:

- Beam test SFS-EN 14651 (six samples per particular SFRC)
- 5-point slab bending tests of slab (four slabs)

1.5 Thesis Structure

This research project follows the following pattern:

<u>Chapter 1: INTRODUCTION</u>

An introductory chapter translating the general and brief knowledge about SFRC.

<u>Chapter 2: LITERATURE REVIEW</u>

A detailed overview of research work carried out relevant to SFRC. The main focus will be on the effect of different material constituents, types and mix proportions on the behavior of mix, and practical existing applications.

<u>Chapter 3: SELECTION OF POTENTIAL APPLICATIONS IN FINNISH INFRASTRUCTURE</u>

The chapter includes selected potential uses of SFRC in Finnish infrastructure. A brief elaboration with reasone of selecting such infrastructural system.

Chapter 4: EXPERIMENTS

This chapter says all about the preliminary tests performed to get the optimized and required properties of SFRC mix. Besides preliminary tests, major tests are also included in this chapter.

Chapter 5: TEST RESULTS AND CONCLUSION

The results evolved from tests are mentioned and discussed in this chapter. The results are analyzed and concluded.

References

Appendices

CHAPTER 2 : LITERATURE REVIEW

2.1 General Background of FRC

The results concluded in many research article about steel fiber reinforced concrete (*SFRC*) are mentioned in this section. The effects of material constituents effecting the properties of concrete mix and different behavior of concrete mixes are discussed.

Concrete is a mixture of cement, sand, aggregates and acts as a solid unit when placed and cured. The compressive strength of concrete is the main cause of its abundant use in construction industry. Besides, concrete is brittle in nature, lacking flexibility and ductility which is often required from a material to be used in structure liable to bare tensile loads. For making concrete ductile, fibers are introduced which adds extra tensile strengths to concrete. Fibers were in use from long ago in bonding material efficiently. Modern technology enabled us to add multiple types of fibers to enhance its tensile bearing capacity and add a ductile nature.

A variety of fibers are used to transmute concrete´s properties. Steel is the most widely and abundantly used amongst other fibers. The main binder remains cement along with other supplementary composite material to add some special properties to the mix.

Water-cement ratio has always been an active part of concrete as it plays a vital role in the durability, workability and strength of concrete. Steel fibers, when added to concrete, makes it stiffer and reduces the workability. In fiber reinforced concrete, w/c ratio is usually kept moderate and in-between both extreme ends. From research articles, it was concluded that the range of w/c ratio in SFRC varies from 0.4-0.7 depending upon the focusing property. *Wasim et al. 2018* states that using lower w/c ratio [0.35-0.45] enhances the mechanical properties of SFRC by greater margin. *Chavez et al.* [*2017]* concludes that using higher w/c ratio [0.7-0.8] can result in the surface corrosion of up to 1mm depth which can be diminished if the w/c ratio is decreased. Furthermore, w/c ratio greatly depends upon the followability of SFRC as the addition of fibers stiffens the concrete mix and reduces workability. To enhance the workability of SFRC, w/c ratio is kept moderate with the addition of super plasticizers. Adding water is not always the best remedy as it compromises the viscosity and may cause segregation. Furthermore, excess of water can also lead to balling-effect as there is not enough viscosity to keep steel fibers separated individually.

The percentage of fibers is also of utmost importance. Generally, 0-2% fibers to the total volume of concrete are used for structural purposes. Such an addition to concrete enhances compression, flexural, tensile, shear and impact resistance strengths. Extra dosage can also be introduced to extra modify required properties. Greater percentage of fibers means lesser bonding material which can result in weaker compressive strengths because there is not enough bonding material to grip fibers and enhance the strengths resulting in pull-out phenomena.

Aspect ratio [a/d] of fiber is of keen interest. Mechanical properties are greatly influenced by aspect ratio in a direct relation [*Wasim et al. 2018*]. In a report *ACI [544-1R-96*] states that the concrete and steel bond is directly dependent on the aspect ratio and suggests that the aspect ratios from 20 to 100 are preferred to be used. Along all the mechanical properties, flexural strength is greatly affected by aspect ratio.

Steel fibers are present in a variety of shapes and sizes. Research and experiments had shown that steel fibers with tapered heads and crimped results in better strengths then straight steel fibers. Furthermore, *Grija et al. [2016]* states that the crack control parameters is dependent upon i) Fiber percentage, ii) Bond strength, iii) Balanced fiber pull-out and rupture strength, iv) Fiber aspect ratio.

2.2 Fiber types and classification

According to *Naaman [2003]*, fibers used in cementitious composites can be classified with regard to;

1. Origin of fibers: According to origin, fibers can be classified as;
   a. Natural organic (cellulose, sisal, bamboo, jute etc)
   b. Natural inorganic (asbestos, wollastonite, rock wool etc)
   c. Man-made (steel, glass, synthetic etc)
2. Physical/Chemical properties: Fibers are classified based on their physical/chemical properties such as;
   a. Density
   b. Surface roughness
   c. Flammability
   d. Reactivity/Non-reactivity
3. Mechanical properties: Fibers are also characterized on the basis of their mechanical properties;
   a. Specific gravity
   b. Tensile strength
   c. Elastic modulus
   d. Ductility
   e. Elongation to failure
   f. Stiffness
   g. Surface adhesion
4. Shape and size: Classification of fibers is also based on geometric properties;
   a. Cross-sectional shape

b. Length
c. Diameter
d. Surface deformation

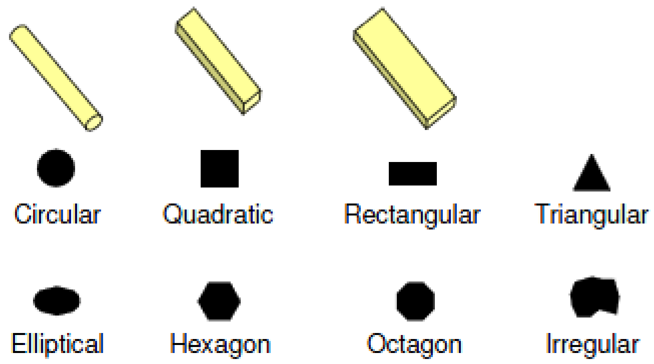

Figure 2: Cross-sectional geometries of fibers [*Löfgren 2005*]

2.3 Fiber Reinforced Concrete

2.3.1 Material used for steel fiber reinforced concrete

Some common materials used for SFRC production are mentioned in detail.

2.3.1.1 Cement

The basic bonding material of SFRC is Portland cement. The quantity of binder in SFRC is larger than that used for conventional concrete. So, the type of cement must be considered keenly to be used in SFRC. If we were targeting high strengths, cements with low calcium aluminates indicates better results for manufacturing high strength concrete [*Richard et al. 1995*]. For better rheological and mechanical performances, high silica-modulus cement is preferred [*Aitcin et al. 1991*].

Strength of cement can be predicted by its type. Compressive strength is directly associated with the type of cement, which is the core property required. As the strength enhances with smaller water-cement ratio, such type of cement shall be selected which demands lesser water consumption with greater flowability. The water demand refers to Blaine fineness value and chemical composition of cement [*Hoang et al. 2016*].

Workability of SFRC is a bottleneck property and needs adequate care and precision while calculating and proportioning. *Bonneau et al. [2001]* concluded his research by stating that coarser cements with low C_3A (tri-calcium aluminate) content results in better workability and requires lesser super-plasticizers compared to using fine cement. Selecting higher strength fine cement class will not end up in substantial enhancement of mechanical properties due to the higher amount of un-hydrated cement content [*Abbas et al. 2016*].

2.3.1.2 Sand and Coarse Aggregates

The granular portion of concrete paste is related to sand and aggregates. Coarse aggregate, in normal concrete, serves as the main rigid skeleton. The initialization of cracks starts with the breakage of bond between coarse aggregate and cement paste [*Richard et al. 1995*]. Further, the research article proposes that the size of the crack is directly proportional to the diameter of the inclusion. Reduction of the aggregate´s size results in minimization of micro cracks due to chemical, thermo-mechanical and mechanical forces significantly.

The optimization of mix with reduced coarser aggregates results in a dense and homogeneous concrete paste exhibiting high mechanical properties [*Richard et al. 1995*]. For stronger and high bonding strength of concrete, gradation of constituents will be done with lesser proportion of coarser aggregates or with using lesser aggregate size [*Cwirzen et al. 2007*]. After the first crack, the energy absorption capability of SFRC depends upon the thin aggregate percentage in the mixture, w/c ratio, and fiber content and fiber type. But does not depend on the thick aggregate maximum size [*Al-Ghamdi et al. 1994*].

Extensive experiments were performed by *Sobuz et al. [2016]* for describing the effect of different types of sand and aggregate sizes. The results showed inverse relation between the fineness modulus and compressive strength of concrete. Addition of coarse aggregates beyond the CA : FA ratio of 0.5 does not affect the mechanical properties negatively rather resulting in lesser workability and compressive strength.

2.3.1.3 Supplementary cementing materials (SCM)

Supplementary cementitious material play its role in adding extra mechanical features to the mix depending upon the requirements. Furthermore, they are also used to replace the main bonding material (cement) by some quantity to make mix cost effective. Cement clinkers can also be replaced by Supplementary cementing materials. Recent practices has shown decrease cement up to 77-85 % and can be subjected to further decrease in future [*Schneider et al. 2011*].

SCMs can be ground granulated blast furnace slag (GGBS), fly ash, silica fume, calcined clays and natural pozzolans. *Randl et al. [2014]* also proposed the same view on the environmental aspect of cement, if replaced with SCMs, will result in a lesser distorted and polluted environment. His research also mentioned that up to 45 % of cement can be replaced with SCMs without deterring the mechanical properties of concrete mix. *Ghafari and Costa [2012]* concluded their research in stating that replacement of silica fume by ground granulated blast furnace slag do not cause any degradation of the mechanical properties and porosity of concrete. Resulting is a much denser paste which is more resilient to autogenous shrinkage at early age.

In the context of sustainability, the matter of CO_2 production is also of greater concerns. Cement produces 5% of total carbon dioxide globally through its manufacturing process. SCMs play its role there by replacing cement which eventually leads to lesser production of cement resulting in lesser environmental pollution. A report *CEMBUREAU*, which is a European Cement Association, states that the demand of cement is increasing exponentially and it was estimated around 3.6 billion tons in 2012. Such a huge and increasing demand is alarming and needs to be tackled and replaced. Cost effectiveness is not the only root cause of using SCMs, it also decrease the evolution of CO_2 produced in the production of cement resulting in a green environment and reduced pollution [*Schneider et al. 2011*].

Besides mechanical properties, SCMs effect rheological properties to greater extents. Especially, the flowability of concrete mix. Concrete mix shows greater flowability if fly-ash rather slag is been added which is much finer than cement particle. *Li and Wu [2005]* suggested that the flowing property of fly ash is due to its spherical particle shape. *Wei, Handong, and Binggen [2003]* also concluded that the lubricating nature of fly-ash is due to its spherical particle shape. Furthermore, SCMs can also effect the water consumption. Fly-ash requires lesser water resulting in greater compressive strength [*Li and Wu 2005*].

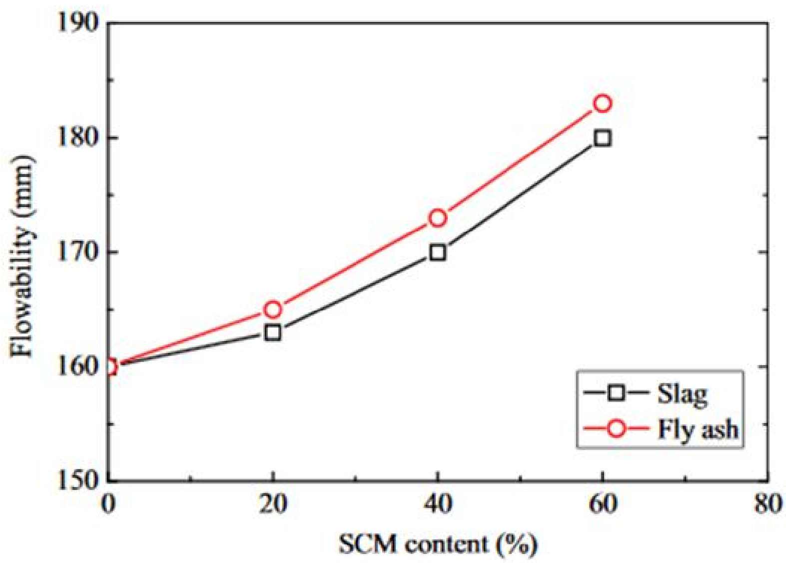

Figure 3: Effect of SCMs on the flowability of concrete mix [Wu et al. 2017]

2.3.1.4 Steel Fibers

Concrete has a brittle nature and instantaneous failure phenomena. So, it is mandatory to introduce a material with greater tensile strengths to withstand tensile loads. In approximately all cases, concrete is susceptible to bare tensile loads therefore the need of tensile strength is mandatory.

Reinforcement is the most common and widely used case in which the tensile strengths of concrete is enhanced by incorporating it with steel. Such approach is usually applied and can be noticed in all kind of structural members. The zone of concrete specimen where tensile loads are meant to target is reinforced with steel.

Steel fibers acts the same way as conventional steel reinforcement with a slight different approach. Steel fibers hold the specimen tight and add ductility to concrete matrix. Concrete, now, can bare much more loads due to the bridging effect provided by steel fibers between the concrete matrixes.

Steel fibers are vastly used nowadays in the construction industry as its use is versatile and effective. The difference lies in their manufacturing process. Types and groups are dedicated by *ASTM A-820* as per manufacturing procedure adopted such as;

- Type-I: Cold drawn
- Type-II: Cut sheet
- Type-III: Melt extracted
- Type-IV: Other fibers

Different steel fibers have different lengths and diameters. Such dimensions directly affect the resulting mechanical properties. Especially, aspect ratio and yielding strength of steel fibers is of greater concern. It is stated that the fiber embedment length into the mortar matrix, aspect ratio and fiber orientation, greatly influences the fiber pullout response [*Steel Fiber Reinforced Concrete, Harvinder Singh 2017]*. Furthermore, the effectiveness of steel fiber in a concrete matrix is also dependent upon the physical shape. Some major physical properties of fibers with direct influences on mechanical properties are mentioned in Table 1. *Małgorzata et al. [2017]* researched about the effect of different shaped steel fibers on the mechanical properties of concrete mix and found out that different shaped fibers results in different mechanical properties.

Table 1: Physical properties of steel fibers [*ACI 544.1R, Ingemar et al. 2005]*

Type of Fiber	Length	Diameter	Aspect Ratio	Specific gravity	Tensile strength	Elastic modulus	Ultimate elongation
	[mm]	[μm]		[g/cm³]	[MPa]	[GPa]	[%]
Steel	6-76	5-1000	20-100	7.85	200-2600	195-210	0.5-5

Steel fibers are introduced into concrete mix in accordance with volumetric percentage. *Doo-Yeol et al. [2015]* did extensive testing to experience the behavior of different percentages of SFRC on different concrete strength classes. His results are mentioned in Figure 4. *Elias et al. [2015]* concluded that excessive steel fibers refers to excessive mechanical strength but it can also leads to negative impact as there will be lesser concrete matrix to hold fibers. *Huang and Zhao (1995),* states that steel fibers exceeding 2% by volume can have adverse effect on the compressive strength of fiber reinforced concrete due to the lack of concrete matrix holding fibers.

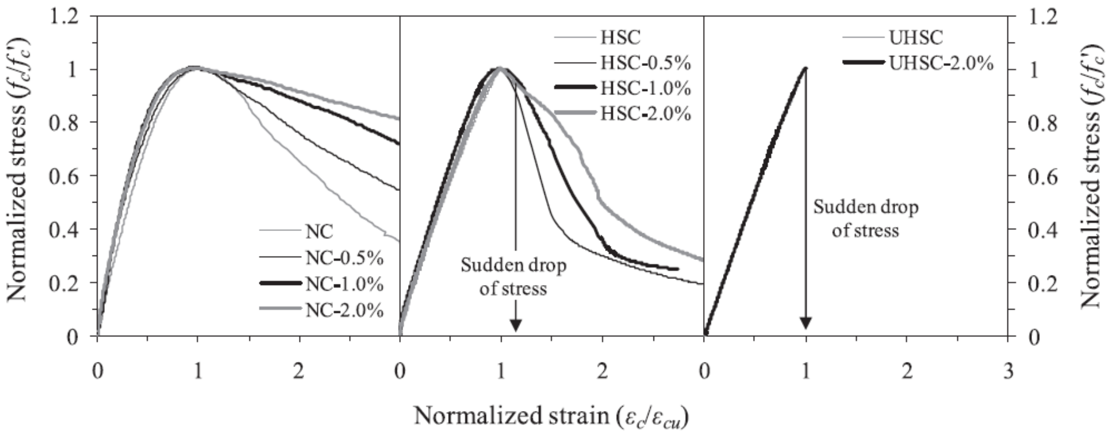

Figure 4: SFRC stress-strain plots [*NC: Normal concrete, HSC: High strength concrete, UHSC: Ultra high strength concrete] [Doo-Yeol et al. 2015]*

Besides manufacturing procedure, steel fibers are also classified according to their shape and size. Some common steel fiber shapes are mentioned in Figure 2. Deformed shapes are preferred due to their extra mechanical performances. Straight fibers are not used widely as the pull-out phenomenon happens very soon decreasing the dowel effect. According to *Joo-kim et al. 2008,* steel fiber with twisted and hooked geometry shows better flexural results compared to any other fibers.

Steel fibers are very efficient in controlling the cracks. Cracks start to occur after concrete is placed and let to be cured, especially when drying. Such cracks are caused due to autogenous shrinkage etc. Steel fibers hold the particles tight acting as anchors providing dowel effect. Hence, provide the concrete some extra ductility and strength. Dowel effect also leads to prolonged durability and better health of concrete.

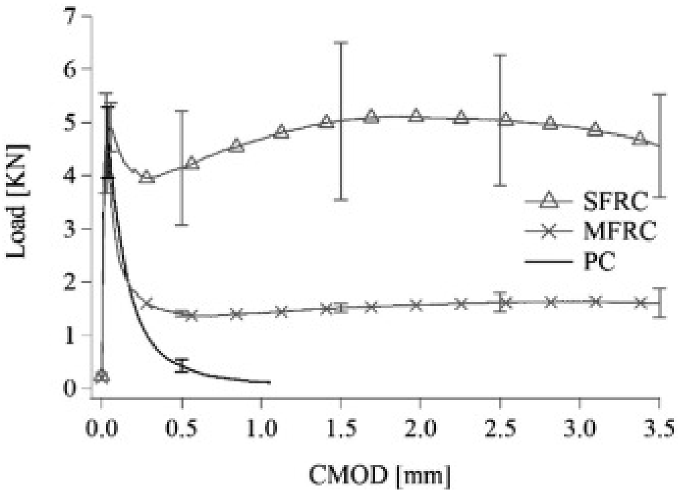

Figure 5: Load vs CMOD of different concrete mixes [*F. Isla et al 2015*]

Tensile yielding strength of steel fiber is of utmost importance. *ASTM A-8210* suggests steel fibers with a minimum tensile yielding strength of 345 MPa while *JSCE [Japanese society of Civil Engineers]* suggest 552 MPa of tensile yielding strength. Steel fibers are available up to 2068 MPa of yielding strength.

2.3.1.5 Superplasticizers

The use of admixtures allow us to use concrete in a variety of fruitful situation. Admixtures can enhance workability, strength, freezing and thawing resistance and compressive strengths [*Steel Fiber Reinforced Concrete, Harvinder Signh 2017, 7-8*].

Water is required to concrete to undergo hydration process. It effects many essential properties of concrete directly and significantly. But, excess of water can alter concrete´s properties negatively and can result in lesser durability, effectiveness, and applicability. For such case, superplasticizers are introduced in concrete to replace the excessive use of water without defecting concrete´s mechanical properties. Many types of superplasticizers are present in the market nowadays exhibiting different ranges of water replacement.

Superplasticizers are nearly mandatory to be used in a steel fiber reinforced concrete mix. Especially, a medium-to-high range water reducing admixture is necessary to achieve the required workability of SFRC. Hence, water-cement (w/c) ratio is decreased to the water quantity required only for the hydration process rather achieving workability too. *Plank et al. (2009)* studied the effect of two types of Poly-carboxylates [PCEs] on cement and silica mix with lower water-binder ratio. He found that Methacrylate ester co-polymers dispersed well allowing greater workability while Allyl ether co-polymers dispersed well in silica and provided greater workability. The research suggested the use of both in a combine cement-silica mix.

2.4 Steel fiber reinforced concrete

Steel fiber reinforced concrete is a composite material made up of a cement mix with embedded steel fibers. Steel fibers, distributed randomly in cementitious mixture, can have various volume fractions, geometries, orientations and material properties [*Löfgren (2005]*.

Research has shown that fibers with low volume fractins (*<1%*), in fiber reinforced concrete, have an insignificant effect on both compressive and tensile strength [*Löfgren 2005]*. They however, contribute to the toughness and post-cracking behavior of concrete. This behavior can be measured as a flexural tensile strength and determined through different experimental test methods, where three point and four point bending tests are the most commonly used methods. Other noteworthy methods are wedge splitting tests (WST) and uni-axial tension tests (UTT).

Experiments, performed by *Özcan et al. (2009)*, on steel fiber reinforced concrete beams with varying fiber dosages, revealed that fibers have a negative impact on compressive strength and modulus of elasticity, as both decreased with increasing fiber dosages. The experiments however showed that the fibers have a positive effect on the toughness of the specimen, as the toughness increased with increased fibers dosages.

Today, fiber reinforced concrete is mainly used for industrial floor purposes, where the slabs on-grad are exposed to heavy repetitive loads from trucks and lifts, in order to increase the durability of grad-slab and increase the strength against cracking. Another area where fibers are used in in tunnel linnings, where fibers contribute to increased strength against shrinkage and reduction of permeability as tunnels are often subjected to water or soil loads.

2.4.1 Post-cracking behavior

Steel firer reinforced concrete has its speciality when it comes to cracking. The behavior of fiber reinforced concrete varies with composition and can have a softening or hardening behavior, see Figure 6. Post crack hardening allows multiple cracks before failure while in post crack softening there is considerable reduction in strength after the first crack allowing no further cracks.

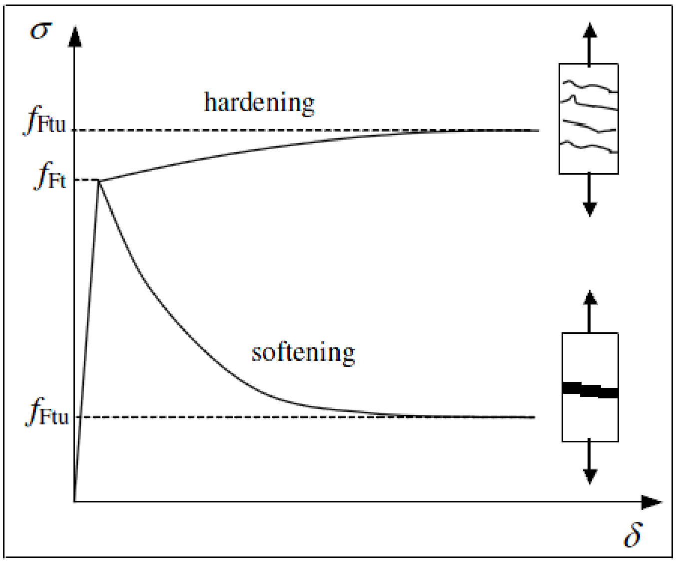

Figure 6: Post cracking behavior of FRC in tension *[Jansson 2008].*

2.4.2 General Mix procedure

Concrete is a composite material of cement, sand, aggregates and water. Mix-design refers to a particular pattern in which all these materials/ingredients are mixed together to form a workable and effective composite material. Generally, wet-mixing and dry-mixing procedures are adopted for concrete production. *Buquan et al. (2003) and Sahmaran et al. (2007),* concludes that each mixture composition has its own mixing sequence, percentage of water, and chemical admixtures added with time intervals, and total mixing time.

For fiber reinforced concrete, the procedure may alter a bit or can be the same depending upon the research carried out. *Liberato et al. (2007)* states the same procedure as of ordinary concrete quoting that cement, fly-ash, and superplasticizers can be added to water-aggregates paste to form self-consolidating concrete.

Beddar et al. (2003) states that for the optimization of rheological and mechanical properties of fiber reinforced concrete paste, a bit changed procedure may be adopted i.e. dry mixing of cement and aggregates for half a minute, addition of water and mixing for three minutes, addition of superplasticizers and fibers, finally mixing the whole volume for three more minutes. Such a procedure is adopted to minimize the rheological defects that may occur while mixing especially unhydrated cement particle and a homogenous steel fiber distribution.

The problem generally occurs in mixing steel fibers to concrete paste is balling-effect. Steel fibers strangles together rather than being distributed and scattered homogenously. For neglecting such an effect, steel fibers are introduced in stages rather than direct pouring. Balling effect is also dependent upon the volume intrusion. *Abibasheer et al. (2015),* proposes a procedure in which all aggregates are mixed for 30 seconds followed by mixing sand for 45 seconds, cement and cementing supplements (SCMs) added and mixed for 4.5 minutes, steel fibers were introduced slowly to neglect balling effect, 80% of water is added while mixing and the rest of 20% is mixed with super-plastisizers (SP), further 2 minutes of final mixing will result in a perfectly distributed steel fiber reinforced concrete. *Chavez et al. (2017),* concludes that steel fibers can only be added once the mix is sufficiently fluid to avoid balling effect. *Faisal et al. (1990),* states that the increase of aspect-ratio, percentage of fibers by volume, and size and quantity of coarse aggregates will intensify the balling tendencies and decrease the workability.

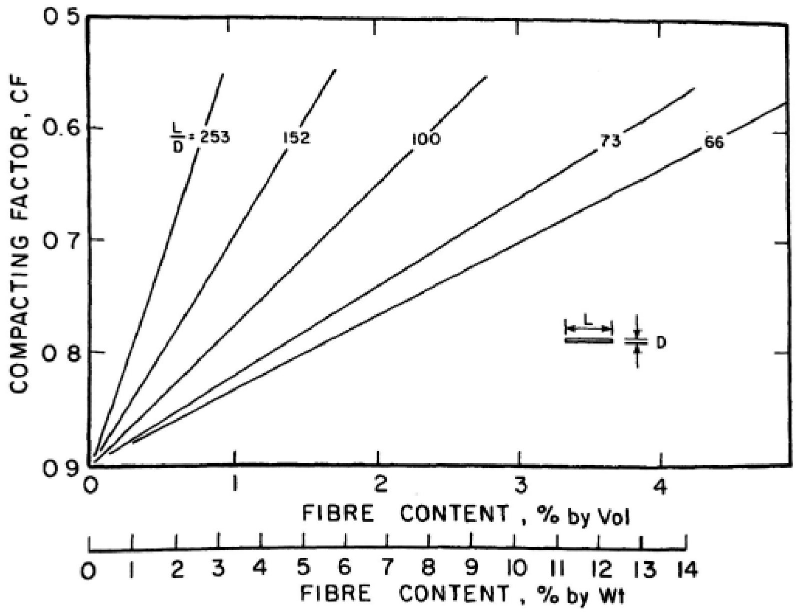

Figure 7: Effect of fiber aspect ratio on the workability of concrete [*Fiber reinforced cementitious composites, second edition, 2007]*

In fiber reinforced concrete mix, the maximum aggregate size is usually kept small to get a workable paste. Altering the gravel-sand relation can result in enhanced workability and well-finished concrete. *Huang et al. (1995)* established that the use of an aggregate with a maximum size of 40 mm in concrete will perform the same way as a concrete made with maximum aggregate size of 10, 15, and 20 mm. Further, they stated that the use of comparatively smaller aggregates will result in greater cement consumption which can lead to excessive contraction cracking. They also mentioned the use of less amount and smaller size of thick aggregate can result in a concrete mix more susceptible to abrasion damage.

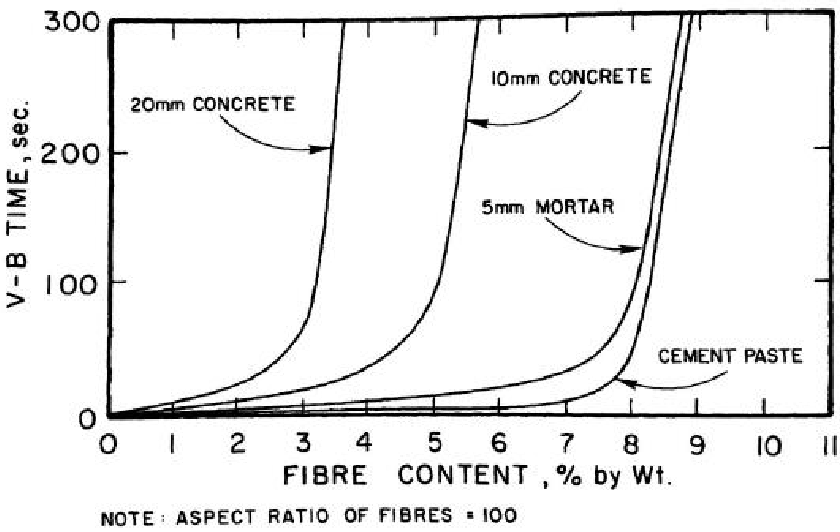

Figure 8: Workability versus fiber content for matrices with different maximum aggregate sizes [*Fiber reinforced cementitious composites, second edition, 2007*]

2.5 Advantages of Steel Fiber Reinforced Concrete

Concrete is hard but brittle material. The failure phenomenon of concrete is also debatable due to its sudden and instantaneous failure nature. Such sudden failure occurs because of the lack of tensile strength. Concrete is efficient while bearing compression loads but it cracks/fails when experience tensile load. For such purpose, reinforcement is induced to add extra tensile load bearing capability to concrete.

Steel fibers acts the same as conventional reinforcement by adding tensile load bearing capability while enhancing other positive features too. As of 2001, approximately 80 million cubic meter of fiber reinforced concrete were produced annually. The benefits of SFRC in construction are well-known. However, the potential of the material is not reflected in the number of applications in actual industry practice in UK. This stems from the lack of widely accepted standards for test and design.

Besides, SFRC is of great use with many advantages. The most prime advantage of the SFRC is arresting the cracks. Fibers start acting after the formation of first crack and continue to absorb energy until they are yielded or pulled out [*Adebar et al. 1997*]. Steel fibers specializes in arresting the formed cracks due to tensile or impact loads. Dowel effect allow steel fibers to hold the cracked concrete section and transfer stresses.

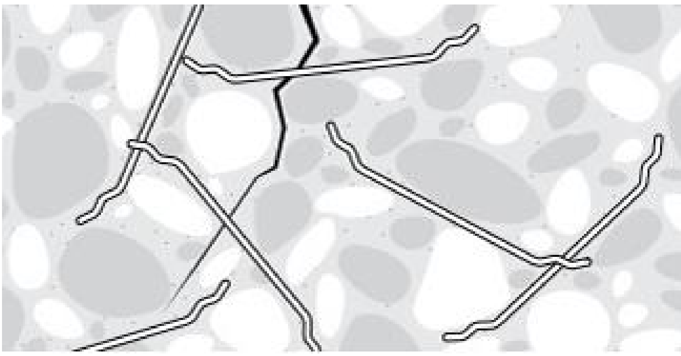

Figure 9: Crack arresting of steel fibers

SFRC acts as a strain hardening material rather brittle as plain concrete (PC). The stress-strain graph clearly depicts the behavior of SFRC and plain concrete as shown in Figure 10. The ductility is directly dependent upon the percentage of inducted fibers by volume. Greater the volume percentage of steel fibers, greater the ductility and vice versa. But excessive inclusion of steel fibers is also hazardous as there must be sufficient concrete matrix to hold the fibers together. Excessive steel fibers will result in less-dense concrete matrix and the softening of matrix can occur quickly rather been delayed by fibers.

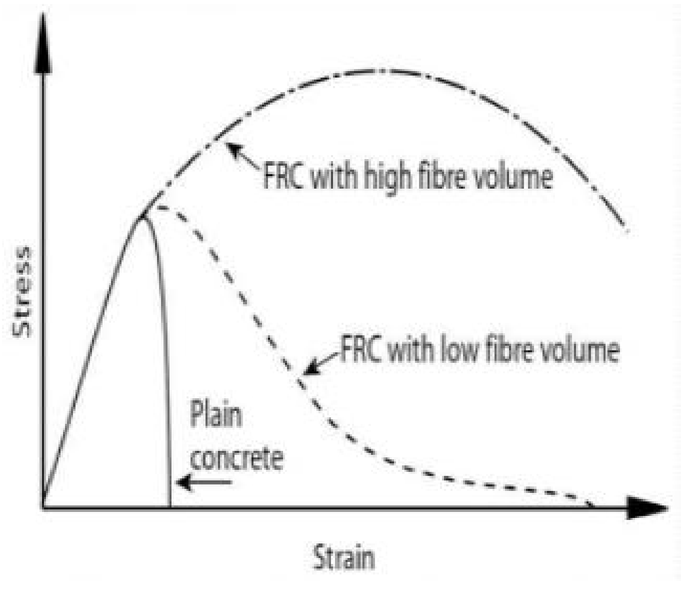

Figure 10: Stress-strain graph of SFRC vs pc

Fiber reinforced concrete saves times by minimizing the labor and reinforcement needed. Construction work is tedious taking a lot of time, effort and energy. For structural purposes, concrete is conventionally reinforced for a better stress distribution and load bearing capability. For reinforcement plotting, extensive and skilled labor is required as well as for setting the form-work. Such an extensive setup consumes prolonged time to set it to perfection. These factors, including time, add up to the total cost resulting in higher expenses. SFRC minimizes the reinforcement hence reducing the cost, labor and assembly time.

ACI 544-1R states that analysis of SFRC slabs, of half-thickness compared to ordinary concrete slab, bears the same vehicular load. Such a reduction refers to the usage of lesser concrete. The extra mechanical strength is provided by steel fibers by enhancing toughness, tensile strengths and resistance to abrasion. Furthermore, the same report concludes 1/3rd reduction in thickness of slab with conventional reinforcement. *Altoubat et al. (2008)* argues that the study done by *Parker et al. (1974)*, 30-50% reduction were obtained for low thickness concretes with the use of higher fiber percentage. *Mohammadi et al. (2009)* determines a 45% of reduction in the rigid pavement thickness by means of 2% use of steel fibers by volume. *Ahad et al. (2015)* agree to the deduction of 20-25% of rigid pavement and roller-compacted concrete.

Lesser consumption of concrete can lead to lesser consumption of cement which is producing 5% of CO_2 worldwide. A report by *CEMBUREAU* states the increasing demand of cement should be tackled and controlled for a better and eco-friendly environment. Sfrc can play its role by reducing the dimensions of structural elements resulting in lesser use of cement.

SFRC is far more durable than ordinary concrete. Defection of concrete starts with a minor crack which springs in a major crack. Steel fibers act as crack arrestors, splits the cracks into multiple smaller cracks, reducing the probability of acrack to be promoted to a major crack. SFRC has enhanced durability due to reduced cracking phenomena [*Di Prisco et al. (2004), Carpinteri et al. (2007)*]. Permeability also plays an important role reflecting durability. Permeability of denser concrete, w/c ratio less than 0.45, is nearly negligible in an uncracked condition. It becomes significant by the introduction of cracks and increasing crack widths (CMOD) [*Ludirdja et al. (1989), Wang et al. (1997)*].

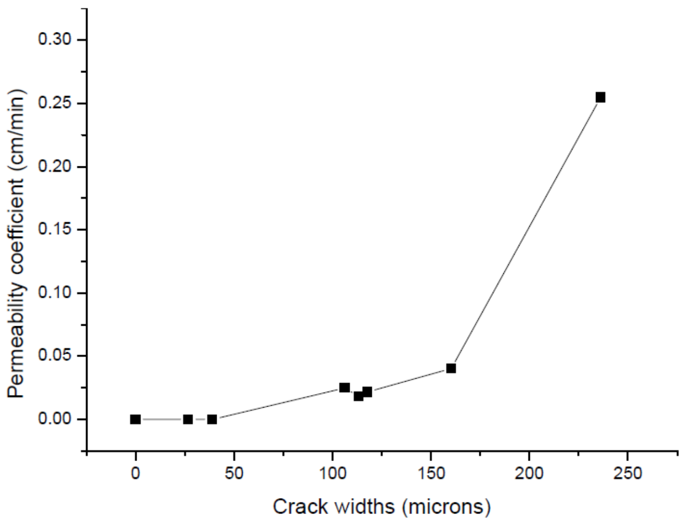

Figure 11: Effect of cracks on permeability of SFRC [Ludirdja et al. 1989]

Crack width of 50μm has negligible effect on FRC but exceeding widths leads to negative impact on the durability of concrete.

Besides, steel fibers also effect the mechanical properties of concrete mix. Inclusion of 0.5-1.5% of steel fibers, by weight of cement, will enhance the flexural capacity of concrete by 3-124% if the aspect ratio was smaller up to 65 [*Wasim et al. 2018*]. *ACE Committee* 544 reports 2.5 times increase in flexural strength by inducing 4% steel fibers, by weight of cement, compared to plain concrete. Shear capacity of concrete can be multiplied 4 times if 1-1.5% steel fibers are used [*Elias et al. 2015*]. Concrete with higher w/c ratio showed 31% enhancement in tensile strength [*Wasim et al. 2018*]. In the article, it is mentioned that use of same quantity of fibers [1-1.5%], a mild increase in compression strength of about 2-8% for lower w/c ratio [0.25] and higher increase of 10-25% in compression strength for higher w/c ratio [0.35-0.45]. *Faisal et al. (1990)* concludes 10-40% increase in toughness of concrete with the introduction of steel fibers. *ACI committee 544* also states an increase of 5-10 times for impact resistance using steel fibers.

Corrosion is always seriously considered while judging the health of concrete. *ACI committee 544* states that steel fibrous mortar exposed to outdoor weathering in an industrial atmosphere showed no adverse effect on the strength properties and corrosion was only limited to the surface. The corrosion effect in SFRC occurs in the fibers located within 1mm on the concrete surface for concrete with w/c ratio of 0.78; whereas the corrosion effect diminishes with lower w/c ration [*Balouch et al. 2010*].

2.6 Applications of Steel Fiber Reinforced Concrete

Since the introduction of SFRC in late 1960s, the use of such concrete composite is increasing steadily. The application of SFRC depends on the ingenuity of designer and builder to use the static and dynamic tensile strength, flexural strength, energy absorbing characteristics, toughness, and fatigue endurance of this composite material.

Some major structural uses of SFRC are mentioned as following;

2.6.1 Cast-in-situ

Runways:

Till 1983, twenty-two airport paving projects were been completed in United States. The main reason behind such is the impact resistant nature of SFRC. Jet wheel puts an impact force when it touches the ground thus requiring a material to withstand the heavy impact force and absorb the transmitted energy. Furthermore, SFRC provides additional ductility and durability. Till now, many runways are constructed with SFRC and the aircraft-parking too.

Figure 12: Runway constructed with SFRC

Industrial floors:

Over 1.9 million square meters of industrial flooring had been constructed in Europe. Shrinkage plays an important role in crack formation when the concrete is supposed to be placed on a wide and vast area. Steel fibers arrest the cracks and transforms the concrete into one solid unit thus reducing shrinkage cracks. The projects mainly included bridge deck overlays and floor overlays. The Honda automobile assembly and office building in Alliston, Ontario, Canada covers $74000m^2$ is done using SFRC.

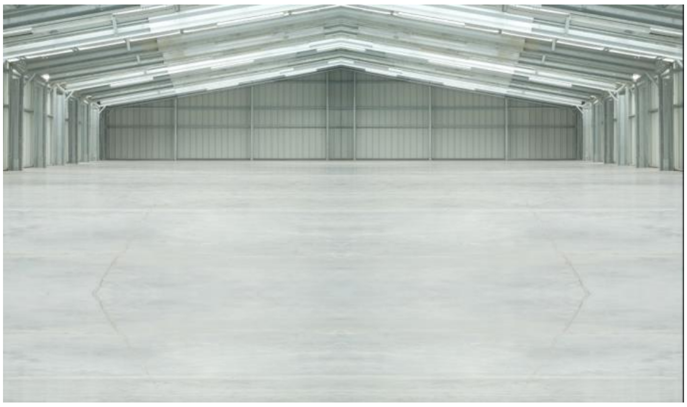

Figure 13: Industrial floors of SFRC

Foundation Slabs:

SFRC has its application in foundation slab too. The shear reinforcement is prominently reduced due to the use of steel fibers. Furthermore, the most effective part is the reduction of thickness in foundation slab. Such slab is usually thick and require heavy reinforcement. The concrete and conventional reinforcement, both, are reduced by introducing steel fibers. Such introduction leads to lesser concrete and steel consumption resulting in lesser cost.

Figure 14: SFRC foundation slab

Encasements:

Usually impact resistant encasement of turbine is made up of SFRC. The structure also consists of conventional steel reinforcement but steel fibers minimizes the thickness. Furthermore, as the water is rushing with high speed and hitting the walls and inserting impact forces, SFRC helps to tackle such situation by providing additional impact resistance to the structure and assure a better health of structure. Impact resistant encasement of a turbine test facility was provided for Westinghouse Electric Crop., Philadelphia.

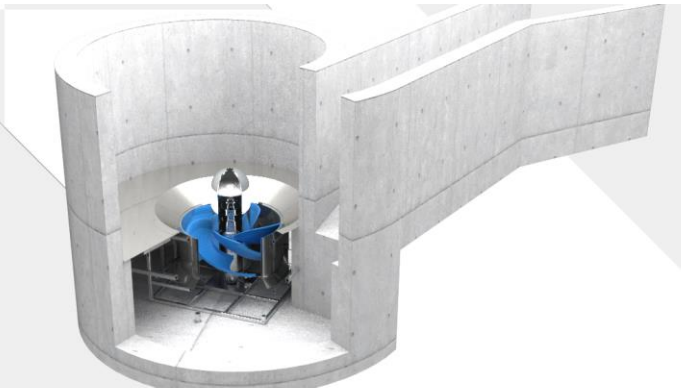

Figure 15: SFRC turbine encasement

Water-works:

Sluice water gates can be applied with the maximum height of 250cm [*Yu Wien et al. 2018*]. Furthermore, SFRC is also efficient in small-scale spillways and embankments. SFRC is preferred for concrete exposed to water due to its denser nature and prolonged durability. Canal lining is often constructed with SFRC due to its extra mechanical properties that adds to the life of the structure and assure lesser seepage and cracking.

Figure 16: SFRC Canal lining

2.6.2 Precast

Dolosse:

Till 1985, 22,900m^3 of SFRC was used for the production of dolosses. The main reason for the use of SFRC was the better wave impact resistance and density.

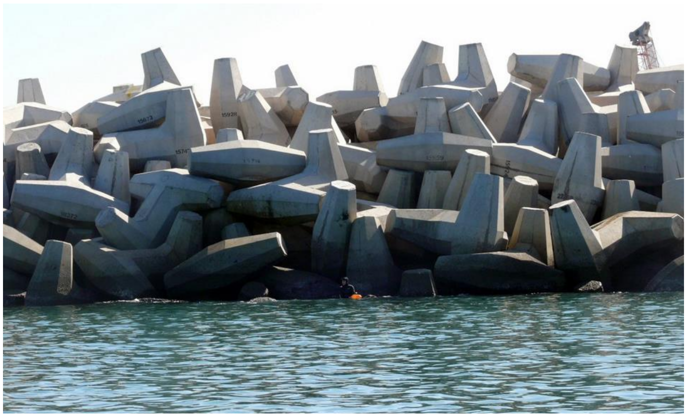

Figure 17: SFRC dolosse

Vaults and Safes:

Thickness of the vault´s walls are minimized due to the application of SFRC with additional toughness. The use of steel fibers by volume is 1-3% for such purposes and conventional reinforcement is reduced by a certain amount. The thinner dimension and lesser conventional reinforcement results in a light weighted block. Due to the denser material, additional shear, impact, and bending resistance SFRC has its application in the making of vaults and safes.

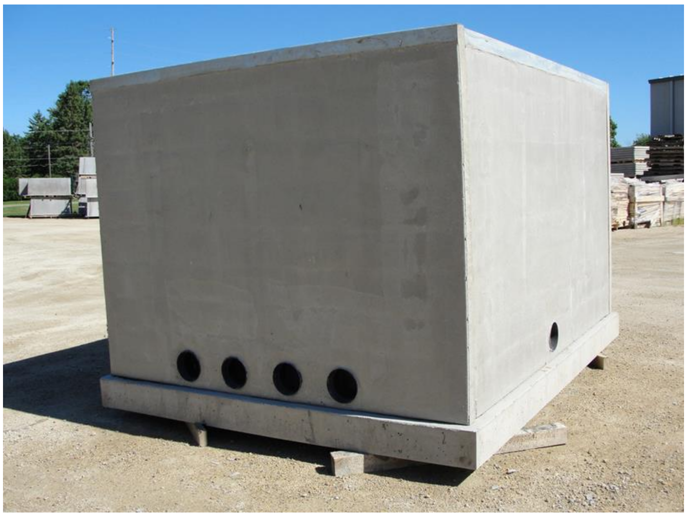

Figure 18: SFRC vault

Mine crib blocks:

Such block units are produced through conventional concrete masonry machines and are routinely supplied throughout the U.S. for building roof support structures in coal mines. Such blocks must be tough and bear extra compressive loads. Furthermore, the ductility and health is also taken into context. SFRC has its applications in the production of such blocks as it provides good health and life span. Additionally, SFRC block doesn´t fail instantaneously rather it went to strain hardening and provides extra time for labors to take the precautionary measurements on time.

Figure 19: SFRC mine crib blocks supporting the mine´s roof

Tilt-up panels:

SFRC is used to produce tilt-up panels up to 24 feet high. In a frame structure where walls are meant to take some load, SFRC wall panels can replace thick panels with heavy reinforcement. The resulting thinner wall panels with lesser converntional reinforcement will have reduced weight with more efficient load taking capability.

Figure 20: SFRC tilt-up panels

Garages:

SFRC is used to manufacture individual family automobile garages skipping the use of conventional reinforcement. Such structure is not supposed to bear heavy loads thus can be categorized under small super-structure category which can be assembled bringing factory-made individual structural members and assembled on site.

Figure 21: SFRC garage

2.6.3 Shotcrete

<u>Ground Stabilization:</u>

In 1974, a trial use of SFRS was carried out across the rock slope of Snake River, Washington. The results concluded were good. Since that time, application of SFRS for stabilization purposes developed extensively and is been used widely nowadays. Steel cage is often planted if the ground is very loose, else SFRS is enough to withstand the load of tough ground strata.

Figure 22: Ground stabilization through SFRS

<u>Thin-shell hemispherical domes:</u>

SFRS applications include thin-shell hemispherical domes cast on inflation-formed structures. Furthermore, artificial rock-scape can also be produced both by dry-mix and wet-mix with addition of silica fume. Conventional steel is used sidewise.

Figure 23: SFRS hemispherical dome

Tunnel lining:

SFRS is a key material concerning tunnel lining. The material holding strength of SFRS is exceptionally greater than ordinary cement mortar which gives SFRS an edge over other composite shotcreting materials.

Figure 24: Tunnel lining with SFRS

2.6.4 Repair work

Dam repairs:

For providing resistance to cavitation, dams are preferably repaired with SFRC. It also play role in minimizing the erosion caused by the impact of large waterborne debris.

Figure 25: Dam repair with SFRC

Pavement repairs:

Approximately 50 bridge decks are repaired with SFRC. Highway pavements can also be repaired with this material providing greater impact resistance and toughness. Additionally, it also controls abrasion and have lesser weathering effect. SFRC repaired pavement will be more effective and flexible. The durability is enhanced by a prominent factor along with extra mechanical properties.

Figure 26: SFRC repaired pavement

Disturbed beams and columns repair:

SFRC has its application in the repairing cracked beams and columns. Many approaches are evolved for such purpose. Usually, extra conventional reinforcement is added along with SFRC for a better load-transfer and durability.

Figure 27: Repair-work with SFRC

2.7 Structures made of SFRC

Tunnel lining at London Heathrow International Airport in 1995:

A connecting tunnel at Heathrow international airport with a length of 1.4km was constructed with steel fiber reinforced concrete. Conventional reinforcement was totally replaced by steel fibers. For additional load bearing, steel fibers with greater aspect ratio were used. Steel fibers reduced the thickness of lining to 150mm thus reducing the total consumption of concrete to a greater margin.

Figure 28: Tunnel lining at Heathrow international airport

Canal lining at Bakersfield, California:

The project was managed by U.S. Bureau of Reclamation. Friant-Kern canal is 152 mile long that conveys water to Fresno, Tulare and Kern counties. Due to the widening of canal, the portion below the road bridge needed special treatment. Due to the greater impermeability of SFRC and additional mechanical strengths, SFRC also reduced the reinforcement by #5 rebars at 12" o.c., and quickened the construction. The result was durable and corrosion resistant lining that will last for many years.

Figure 29: Friant-Kern canal lining

Dolosses by Corps of Engineers in Northern California:

In 1982-1985, dolosse were placed on the coast-line of northern California made up of SFRC to resist the impact of sea-waves. Approximately 23000 cubic meter SFRC were used.

Figure 30: Dolosse on coast-line of Northern California

Taxiway pavement of John F. Kennedy airport, New York.

The taxiway of John F. Kennedy airport was constructed with SFRC in 1999. The main approach of using SFRC was crack-controlling rather getting strength. As jet load is an impact load while landing, which is efficiently tackled by SFRC.

Figure 31: Taxiway of John F. Kennedy airport, New York

Grad-Slab of John C. Lincoln Hospital, Phoenix, Arizona:

New grad-slab was required at John C. Lincoln hospital for parking purposes. The previous slab was torn and cracked. Steel fibers with the dosage of 6 lbs/yd^3 were recommended to replace total conventional reinforcement. Such an approach saved time and cost to greater extent along with additional mechanical strengths.

Figure 32: Grad-slab of john C. lincoln hospital

Mercedes-Benz of Scottsdale Facility, Arizona:

While building new Mercedes-Benz of Scottsdale facility, concrete contractor Heywood Builders sought out an alternative solution to welded wire fabric for reinforcing the facility´s 300-cubic-yard composite concrete/metal deck system. High strength steel fibers with a dosage of 5 lbs/yd^3 was applied. Such system showed greater crack-controlling and crack-resistivity.

Figure 33: Mercedez-Benz of Scottsdale facility

Yankee Stadium walking pathways, New York:

While designing Yankee Stadium, the baseball team´s owner wanted to create a state-of-the-art facility that would surpass the existing structure while embracing traditions. A top priority was to install a concrete walkway, topping and floor that wouldn´t crack. Structure engineers came up with a solution of using steel fibers (macro-fibers) as an alternative to wire-mesh reinforcement. Such an introduction resulted in lesser plastic and drying shrinkage cracks. A smooth and durable concrete pathway slab with a crack-free appearance was achieved.

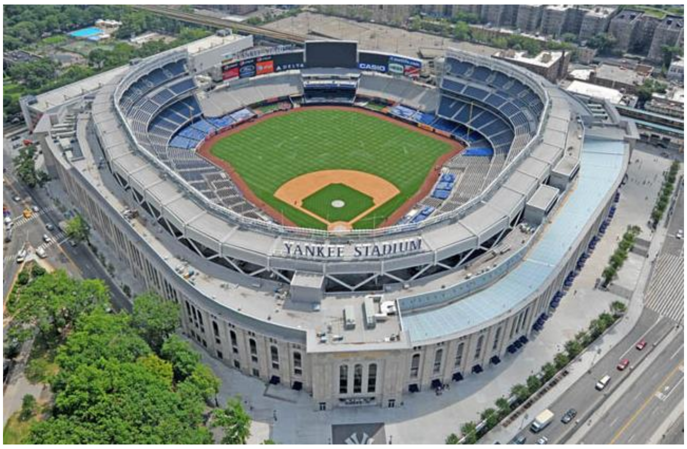

Figure 34: Yankee Stadium, New York

Joint-less Grad-slab in Larapinta, Australia:

Douglas constructions have constructed a homogenous and joint less industrial grad-slab. Joints are provided in ground slabs to counter shrinkage and plastic cracks. SFRC allows to neglect joints and cast a homogenous concrete slab. Such casting is trending in the market.

Figure 35: Joint-less grad-slab in Larapinta, Australia

CHAPTER 3 : SELECTION OF POTENTIAL APPLICATIONS

3.1 General description

Following are found to be the most potential applications of SFRC in Finnish infrastructure. Few of many are pointed out which will be further narrowed to a single application.

SFRC has a growing significance in construction industry and is used in many ways nowadays. Its application is vast as it adds additional mechanical and physical properties to a structure member.

3.2 Potential applications

3.2.1 Industrial ground slabs / Grad-slabs

Most buildings used for manufacturing, distribution, and storage have concrete floors placed on ground. The main emphasis of the design of the slab will be on counteracting crack formation and a better health throughout the designed life. Plastic cracks can appear before the concrete is settled properly due to the internally exerted stresses. Engineers worked to develop durable and cost-effective industrial floors for which heavy conventional reinforcements were induced. Modern technology recommends the use of steel fiber reinforced concrete for grad-slabs as it improves many features such as mechanical properties and health of concrete [*Zhang et. al 1999*].

Industrial floors are casted in parts to minimize shrinkage and plastic deformations. SFRC allows to cast greater spans without a joint. This is due to the steel fibers which bares the internal stresses evolved while the matrix is undergoing hydration. Such feature of SFRC minimizes the labor work and extra costs while providing a homogenous and smooth looking floor.

Conventional reinforcements are usually used to counter the flexural and shear forces while using ordinary concrete. Using SFRC allows to cut-off conventional reinforcements to a certain percentage or may replace it. Shear reinforcement can be replaced totally with the use of SFRC. Rebars formation is often complex and has greater assembly time. SFRC reduces the time, replaces conventional reinforcement, and add extra mechanical properties [*ACI 318-11 commentary R11-4.6.1(f)*].

As steel fibers are distributed homogenously throughout the concrete matrix, results in a more uniform concrete composite. SFRC has significant impact resilience and the uniform matrix refers to improved impact resistance at every spot [*Rishi et al 2004*].

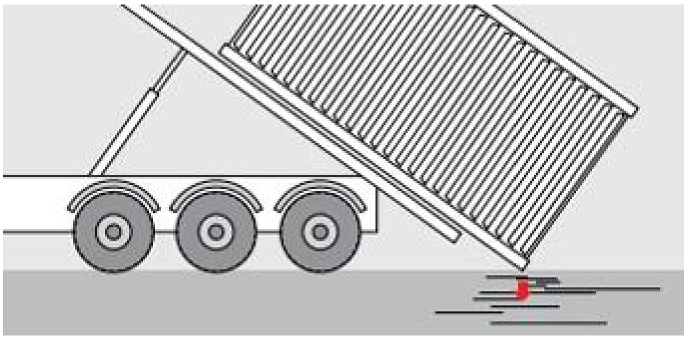

Figure 36: Impact loads on industrial floors

SFRC bares load even after it has been cracked. Post-crack load taking ability is a special feature and helps in many ways. It provides time to come up with fixing strategies and remedies. After cracking, steel fibers tend to resist the cracks propagation and distribute major crack into smaller minor cracks.

All the features described, leads to a cost-efficient, quick, durable, and stronger grad-slab.

3.2.2 Beams / Columns

Beams and columns are structural members of a frame structure. Ordinary concrete along with heavy conventional reinforcement is used in such structural members. The strength of these members is of immense importance and their failure can lead to disasterous situation.

SFRC is mainly used due to the recommendation of modern technology. SFRC already consists of steel fibers will reduce the steel rebars, meant to be used to counter the resulting load stresses. SFRC is effiecient in replacing shear reinforcement while adding extra flexure strength to concrete member [*ACI 318-11 commentary R11-4.6.1(f)*].

Cracks appear when the structure experiences excessive loads. Those loads can be short-term, long-term or impact. SFRC is efficient in resisting the formation of cracks and reduce the chances of a major crack as SFRC disperses it into multiple minor cracks. Furthermore, SFRC also provides post-crack resistance which help in coming up with remedies or recovering addressed members.

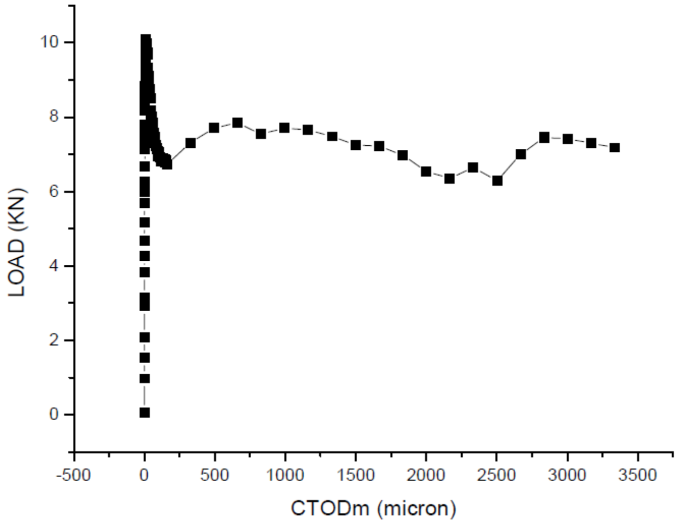

Figure 37: CTOD and load relations of SFRC [*Vasanelli et al 2008*]

Beam casted with SFRC shows more resistive and flexible nature. Besides shear, SFRC also provides greater bending resistances at ultimate load. Load-displacement curve of concrete beams without steel fibers falls much shorter with the increase in displacement which means that the concrete beams with steel fibers possess better ductility.

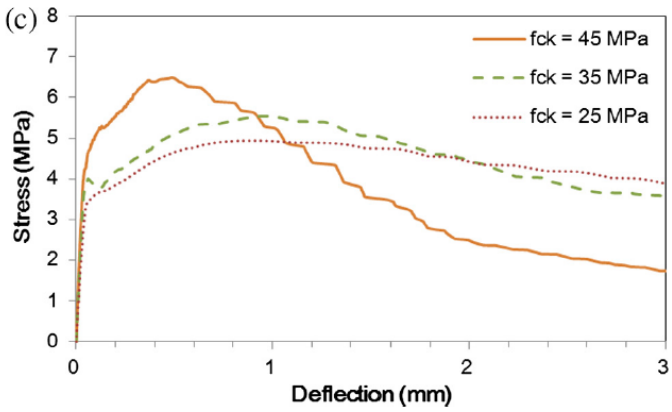

Figure 38: Flexure behavior due to 1% steel fiber [*Jong et al. 2017*]

The part of greater concerns is the joints between a beam and column. The stiffer and non-ductile nature of these joints make it vulnerable to bare and transfer loads adequately. The steel cage at such junctions is complex and costs a lot of assembly time. Replacing ordinary concrete reinforcement with steel fiber reinforced concrete can make these junctions efficient, flexible, and can transfer the load adequately.

Besides, corrosion is also a major factor. Structural members exposed to external atmosphere can corrode if are reinforced with inefficient concrete cover. Corrosion is a slow process but can cause serious damages to a structural member. SFRC is a dense material and reduces corrosion effectively. A member is likely to be corroded, if it is cracked and open to moisture but as SFRC counters the formation of a major crack, by dividing it into multiple smaller cracks, is a valuable solution. CMOD less then 0.1mm cannot cause corrosion. Furthermore, SFRC doesn´t result in bursting or spalling due to corrosion. Only fibers crossing the crack within a 2-3mm rim from the external faces of the specimens exhibit extensive corrosion [*Balouch et al. 2010*].

Concrete cover plays a vital role. As discussed earlier, SFRC is a denser material and structurally more sound than ordinary concrete. There is no need of extra covers i.e. 30-50mm which leads to extra concrete thicknesses. The impermeability of concrete is already discussed to be sufficient. No need for providing thick concrete covers if using SFRC. Such an act leads to lesser dimensions and reduced use of concrete.

3.2.3 Pavements

A pavement structure is comprised of multiple layers. The strength of pavements depends upon the type and vehicular load it is meant to bare. SFRC is widely used throughout the globe for designing rigid and flexible pavements. Some of the mechanical properties such as tensile strength, flexure, impact fatigue, fissure inhibition and energy absorption capacity is substantially increased by using steel fibers.

The durability of SFRC is far greater than that of an ordinary concrete. Besides, SFRC also results in a flexible pavement rather rigid. Flexible nature of SFRC pavement leads to lesser disturbances and prolonged life span.

Complex conventional reinforcement mesh is designed for concrete pavements. Assembling such, takes a lot of time and consumes greater labor. SFRC helps in diminishing a prominent percentage of total reinforcement and add ease to the work.

Pavements are usually exposed to seasonal moisture in the shape of rainfall or drainage. Such moisture can lead to corrosion resulting in major cracks and failure of the system. It is proven often that the corrosion in steel fiber concrete is less than corrosion in conventionally reinforced concrete. The corrosion in SFRC at 1mm depth from external side if the w/c ratio was 0.78 or above [*Balouch et al. 2010*]. It has been discussed that the optimum w/c ratio to neglect corrosion effect in SFRC is 0.48. Further reduced w/c ratio results in diminishing corrosion effect.

Abrasion resistance play a vital role in maintaining the health of concrete pavement. Many fibers have evolved to counter abrasion and provide a smooth, durable, and flexible concrete pavement. Among many, steel fibers were behaving more efficient. The geometry of steel fiber must also be taken into the context. The comparison of different fiber behavior to resist abrasion is discussed in the figure below.

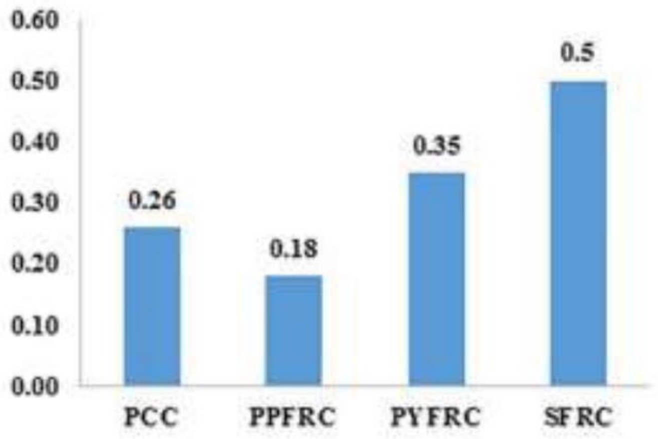

Figure 39: Abrasion resistance analysis [*Bolat et al. 2014*]

*

PCC	Plain cement concrete
PPFRC	Polypropylene fiber reinforced concrete
PYFRC	polyester fiber reinforced concrete

Concrete pavements are usually casted in parts. Dowels are often introduced for a better joint. SFRC pavement allows to cast continuously with no dowels. Steel fibers act as dowel at individual level. Fibers try to retain a solid concrete shape and absorb energy. Hence, a thorough distribution of load happens reducing the chances of creating stress-critical zones.

Conventional reinforcement cause single point crack restraint. Steel fibers can provide continuous crack restraint thus reducing the CMOD (crack mouth opening displacement). Besides, SFRC also provide post-crack strength diminishing sudden failure of a pavement system.

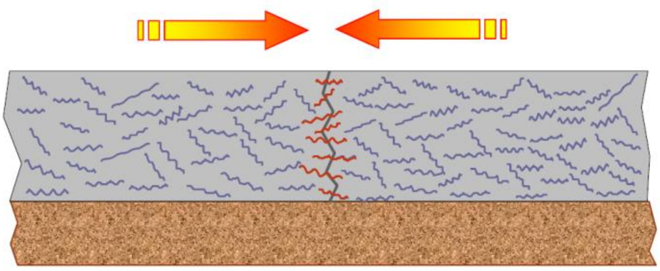

Figure 40: Continuous crack restraint by SFRC in pavement

3.3 Pile Slabs

Piles are usually introduced to a region where earth strata is not of adequate quality and there happens some lag in providing necessary bearing capacity. Piles act as nails dug deep into the strata to provide a firm support and counter the excessive moments and gravitational loads.

In deep foundations, loads are transferred to the slab rested on the piles. Loads are evenly distributed to the piles which further distribute load to the ground. Slab may be a simple floor or a cap on which a pier/columns rests. Vertical structure member transfers the load to slab/cap which is further distributed as mentioned above.

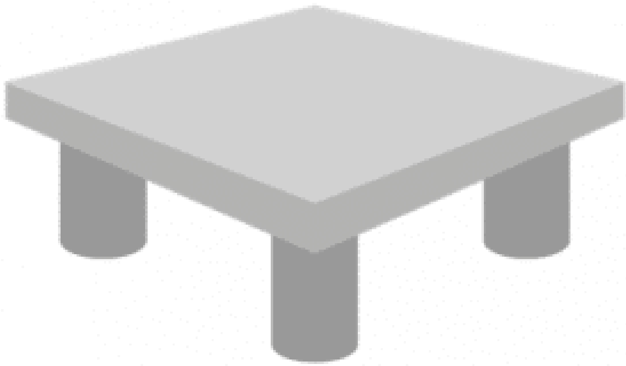

Figure 41: Pile slab

The approach of slab resting on piles is widely used nowadays in construction industry due to its positive aspects. It may be a grad-slab resting on piles due to loose ground condition, a foundation slab resting on piles to distribute the load thoroughly to piles and surrounding strata, and a pier resting on piles under a slab to bear heavy dynamic loads of a bridge or a super structure.

Tradionally, slabs on piles are built using heavy steel bar reinforcement which leads to slow construction work and high costs. Reinforcement density is directly dependent on the load such slab is meant to bear but as such structural system is preferred to bear heavy loads results in denser and complex reinforcements.

As discussed above, such system is preferred for high-rise buildings or bridges. The extra loads produce excessive moments resulting in extra flexural reinforcement. Introducing SFRC has its advantages by cutting off and simplifying complex reinforcement patterns. Steel fibers will be present homogeneously throughout the matrix allowing every bit of concrete to absorb certain amount of energy and reduce the stress level.

SFRC is impressive in minimizing shear reinforcement. A minor introduction os steel fibers to concrete mix can multiply its shear capacity by a signinficant number. *Elias Toubia et al. (2015)* concludes 2.4-6 times higher shear resistance capacity by introducing steel fibers of 1-1.5%.

Durability is of greater concern. The major factors effecting durability of concrete are corrosion, permeability, and cracks. SFRC, being a denser composite material, has lesser impermeability than ordinary concrete and has a signinficant resistance towards corrosion as only the steel fibers at the depth of 1mm from concrete surface are corroded while the rest of matrix remains untouched [*Balouch et al. 2010]*.

Figure 42: Corrosion pattern on exposed side of SFRC block

Cracks are the most dominant part of cocnrete´s durability. Cracks start appearing soon after the final settlement of concrete in the form of shrinkage and plastic cracks. If concrete mix has steel fibers, the stresses produced due to temperature changes (hydration) and settlement is beared by steel fibers resulting in minimized shrinkage and plastic cracks. Furthermore, steel fibers also act as crack-arrestors and provide significant post-crack strength.

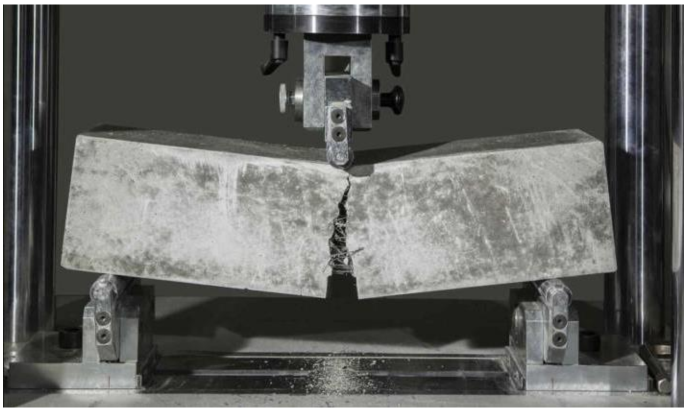

Figure 43: Post-crack strength of SFRC

Introducing steel fibers to concrete doesn´t require much of an effort. A few precautionary measurement can do the job with ease and precision. Besides, conventional reinforcement requires time and effort. Steel fibers are not sufficient to replace heavy conventional reinforcement but can reduced its scope to a prominent level thus reducing the effort and time invested in its assembly. All these factors lead to cost efficiency and maximizing the capital of industry [*Balouch et al. 2010]*.

CHAPTER 4 : EXPERIMENTS

4.1 Introduction:

This chapter includes the experimental program and description of material used to achieve the required results.

The experimental program was set into two parts. The first part was composed of preliminary test to achieve/check the optimum mix-design with differential steel fiber dosages. The main focus of preliminary mix-designs is to achieve maximum flexural, tensile, impact and compressive strength of SFRC. Furthermore, the w/c ratio and use of super plastisizers (SP) is also optimized.

Mix design of concrete was provided by Rudus Oy which is also sponcoring this research project. Furthermore, the percentage of super plastisizers (SP) is optimized to target S-3 slump class.

Final tests are extensive and an extension of preliminary tests. The mixes with the most effective rheological and mechanical properties are finalized and its behavior is studied against compression, tension, impact, flexure, and shear.

4.2 Mix Design:

Mix design provided by Rudus Oy needed to be adjusted for different dosage of steel fibers. The workability of concrete plays a vital role towards its practicality and usage. Many trial tests were performed to adjust the mix design’s workability accordingly.

For such a purpose, slump test was used and S3 slump class was targeted. The ratios of individual ingredients, especially w/c ratio, provided by Rudus Oy were kept constant and iterations were done with differentially increasing super plasticizer content. Workability can also be managed through changing the filler and water content but changing these ratios alters the strength class.

Following Table 2 shows the ratio and amounts of individual ingredrients used for slump tests. Super-plasticizer content is not included and will be elaborated in a separate table.

Table 2: Mix proportions for preliminary tests

Material	Composition by individual weights	Percentage by cement weight	Percentage by concrete weights
	kg/m^3	*Ratio*	*%*
Cement	340	1	14.30
Aggregates	1846	5.43	77.60
Water	193	0.567	8.11

SFRC is a stiffer material. Special measures must be taken to make such stiff material workable on site. As this project doesn´t take air-content into the context so super-plasticizer content is used to make the stiffer material workable. The target slump class is S3 which says the slump must result in the zone of 100-150mm. Several preliminary tests were performed with iterative SP% to set the mix according to S3 category. As stated above, super plasticizer content is adjusted for individual steel fiber dosage to get S3 slump value. Following Table 3 shows the percentage of SP used for different steel fiber dosages.

Table 3: Super plasticizer usage

Steel Fiber *(kg/m^3)*	Super-Plasticizer *(%)*	Slump class
35	0.4	S3
50	0.6	S3
75	0.7	S3
100	0.85	S3

The amount of super-plasticizers increased as the steel fiber dose is enhanced. It is because of the stiffness added due to the addition of steel fibers. The mixture acts stiffer and needs an extra amount of plasticizer to re-adjust the workability.

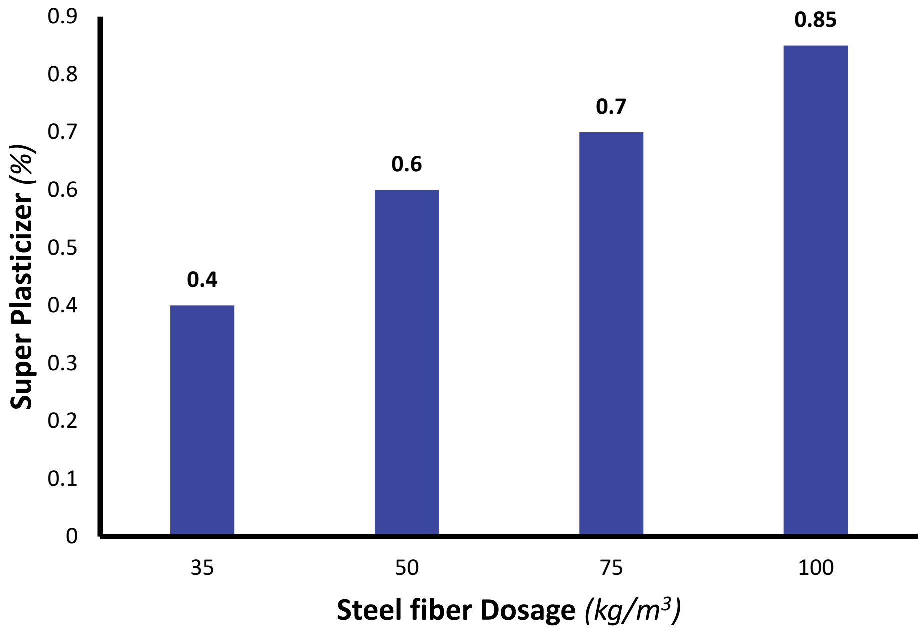

Figure 44: SP% for different steel fiber dosages

4.3 Materials:

SFRC is produced using cement, coarse and fine aggregates, water, and steel fibers. Cement along with supplementary cementing material (SCMs), if any, acts as binder material while aggregates act as fillers. Usually the w/c ratio of SFRC is kept significant enough to assure a smooth flow of mix but super plasticizers are often used. Supplementary cementing material (SCMs) can also be introduced which is strictly dependent upon the requirement of properties and the dosage limitations.

The detail description of different materials used in this research are elaborated in the following sections.

4.3.1 Cement

Cement is the most basic and essential material of any sort of concrete. In SFRC, cement acts as a primary binder material. The cement dosage in SFRC is usually kept greater than in ordinary concrete mix. This addition is due to the need of greater rheological and mechanical properties. Cement reacts with the mineral components and holds the aggregates in a solid shape.

This research uses *Mega-Cement (CEM I 52.5 R)* as a bonding material. Mega cement is fast hardening Portland cement and is used in ready mixed concrete production. Furthermore, it is also used in the industrial pre-cast concrete productions.

Typical properties of CEM I 52.5 R by Finnsementti is provided in the below Table 4.

Table 4: Typical properties of cement and clinker CEM I 52.5 R

Property of Cement	Typical values	Requirement EN 1997-1:2011
1d strength	16-20 MPa	none
2d strength	29-33 MPa	≥ 30 MPa
7d strength	46-52 MPa	none
28d strength	56-62 MPa	≥ 42.5 MPa ≤ 62.5 MPa
Initial setting time	170-230 min	≥ 60 min
Soundness	0-1.5 mm	≤ 10 mm
Fineness	380-420 m^2/kg	none
Loss of ignition	2.1-2.4 %	≤ 5.0 %
Insoluble residue	0.6-0.9 %	≤ 5.0 %
Sulfate content SO3	2.7-2.9 %	≤ 4.0 %
Chloride Cl-	≤ 0.08 %	≤ 0.10 %
Cr6+	0-2 mg/kg	≤ 2 mg/kg

Chemical properties of different types of cement differentiate. The difference of behavior shown by changed cement type is due to the chemical constitutes present. Following table shows the chemical composition of cement (clinkers) provided by Finnsementti.

Table 5: Chemical properties of CEM I 52.5 R

Chemical properties of clinker	%
CaO	60-61
SiO2	18-19
Al_2O_3	5.0-5.2
Fe_2O_3	3.1-3.2
MgO	4.3-4.6

4.3.2 Aggregates

Natural aggregates are used. The maximum aggregate size is kept 16mm as the SFRC mix is stiffer and it is better to use smaller aggregates.

Gradation of aggregates is mentioned in Figure 45.

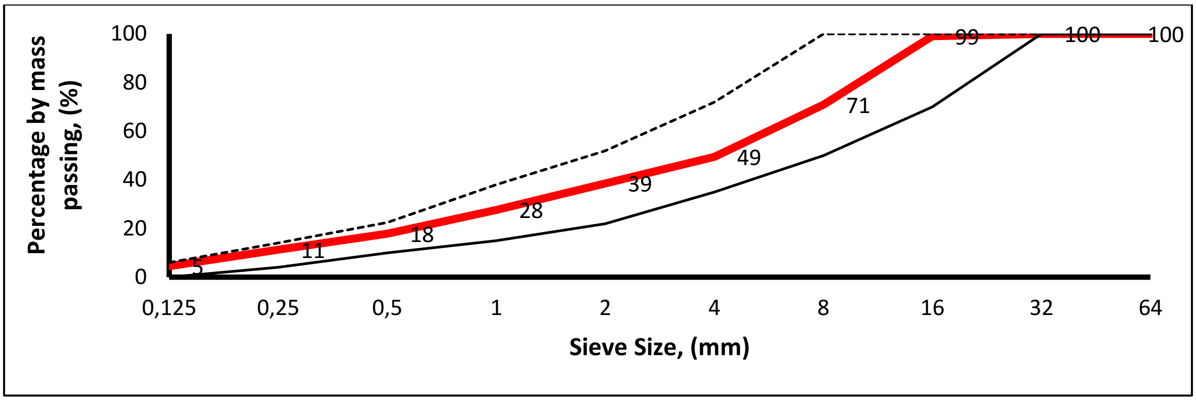

Figure 45: Aggregate´s gradation curve

4.3.3 Steel fibers

There are many steel fibers present in the current market with a variety of physical and mechanical features. The decided steel fibers for our project are deformed steel fibers provided by Bermanto.

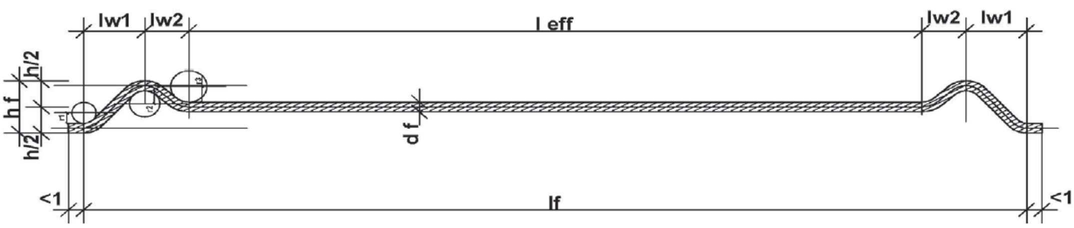

Figure 46: Hendix prime 75/62 (*Bermanto*)

The steel fibers used in this project is *Hendix Prime XP 75/62*. The length of fiber is 62mm with 0.75mm diameter. Every steel fiber differentiates from other steel fibers by the type of steel alloy and yielding strengths. Moreover, the geometry of steel fibers, also, greatly effect its performance and effectivenenss. Aspect ratio [a/d] plays a vital role as many properties are directly linked to it. *ACI 544-1R* states that SFRC in its freshly mixed state are influenced by the aspect ratio of steel fibers, fiber geometry, volume fraction, the matrix proportions, and the fiber-matrix interfacial bond characteristics [*Löfren 2005*]. The rest of technical data is provided in Table 6.

Table 6: Technical data sheet of Steel Fibers

Glued Steel Fibers			Hendix Prime XP 75/62	Tolerance
Fiber diameter	d_f	mm	0.75	+/- 0.04
Fiber Length	l_f	mm	62	+/- 2.0
Hook´s Length	$l_{w1}+l_{w2}$	mm	6.9	+/- 1.0
Hook´s Height	h+h´	mm	4.0	-0.3 / +0.1
Aspect Ratio	l/d	-	83	
Fiber Curvature		%: aL´	max 5%	
Fiber Distortion		^{0}	< 30%	
Number of fiber / kg		-	4651	
Total length of fiber / 10kg		m	2885	
Tensile strength		N/mm^2	> 1500	

4.3.4 Super plasticisers (SP)

Super-plasticisers are admixtures that can be used to decrease the viscosity of concrete and decrease the water demand. Addition of SP increases the workability of concrete or increases the strength when w/c ratio decreases. The durability and density of concrete increases at the same time. Super-plasticisers can reduce the water demand by 5-30% without weakening the workability of concrete.

This project uses *"Saitti-Parmix"* which is produced by Finnsementti. Saitti-parmix combines high water reducing ability and a long workability time. The workability time last approximately two hours in 20^{0}C.

Furthermore, Saitti-Parmix has no negative effects on concrete setting time or strength development. It is specially made for readymixed concrete production and used with crushed aggregates.

Saitti-Parmix is a polycarboxylate ether (PCE) based high range water reducing admixture for all readymixed concrete. This plasticizer is preffered when a prolonged workability time is required.

Saitti-Parmiz can be used in normal and high strength concrete and self-compacting concrete. It is also suitable for air-entrained concrete and shotcrete. Following are finnsementti´s recommendations for saitti-parmix dosages.

Table 7: Finnsemeentti recommendations for using Saitta-parmix

Concrete Type	**Dosage in Percentage** *(%)*
Normal Concrete	0.3 – 0.8
High strength concrete	1.0 – 2.0
Self compacting concrete	1.0 – 2.0

Table 8 elaborates physical properties and technical data of saitti-parmix.

Table 8: Technical data of Saitti-parmix

Colour	Light brown
State	Liquid
Concentration	18%
Chloride content	30kg, 200kg, 1000kg, bulk%
Base	PCE
Operating temperature	> +5 ^{0}C
Storage temperature	> +5 ^{0}C
Shelf-life	1 year

Chemical composition of Saitti-parmix is provided by Finnsemmentti and is included in Table 9.

Table 9: Reported performance levels of Saitti-Parmix

Basic features	Performance level	Technical specifications
Chloride content	≤ 1,0%	SFS-EN-934-2:2009+A1:2012
Alkali content	≤ 2,0%	
Corrosive content	Approved	
Compressive strength	Passes	
Air content	Passes	
Water demand reduction	Passes	
Growth	Passes	
Stability of perseverance	Passes	
Hazardous substance	NPD	

4.4 Preparation of beam specimen

4.4.1 Mixing:

Mix-design was amended for each SFRC dosage and 130 litres batches were mixed filling four beam specimen. Table 10 shows the mixing procedure in detail. Following figure shows homogenous SFRC mix.

Figure 47: SFRC mix

The mixing procedure of SFRC used for this research purpose was a rectified mixing process used commonly for plain concrete mixing. Table 10 shows the time taken while introducing different constituents of mix.

Table 10: Mixing procedure

Description	**Time** *(Minutes)*
Dry mix	0,5
Wet mix	0,5
Super-plastisized mix	4
Steel fiber	2

* Wet mix reflects the introduction of water to dry mix

4.4.2 Curing:

Six beams were required against each dosage. After casting SFRC into moulds, beams are let to be cured for 28 days. Six specimens were casted against every steel fiber dosage on a single day. It must be assured pre-hand to have enough space at curing chamber.

Demoulding was carried out after 24 hours and the specimen were placed in curing-room. The relative humidity was maintained to be 95% to achieve good hydration and promote better concrete strengths. The total curing duration sums up to be 28 days according to the test standard EN 14651.

Figure 48: Beam specimen in moulds

4.4.3 Notch cutting:

Standard states that notch should be cutted after three days of casting or three hours before test is performed. Notch is cut on the longitudinal side-face of beam specimen. The depth of notch is kept 125$\pm$1 mm.

Figure 49: Notch cutting

4.4.4 Knives and transducer:

Hooks are needed to hold transducer firmly. The support must be sufficient enough to support transducer spring and the resulted displacement due to loading.

Figure 50: Glued knives and fixing transducer

4.5 Testing:

Laboratory tests were conducted for both fresh and hardened concrete samples. Slump-tests were conducted for fresh concrete and compressive and flexure strength tests for hard-state concrete.

4.5.1 Fresh concrete tests:

The fresh properties of SFRC can be evaluated through such tests. Flow-test is an essential test which clarifies the flow-ability of concrete referring to the workability of the mix.

4.5.1.1 Slump Test (EN 12350-2):

The test sample of concrete shall be obtained in accordance with EN 12350-1. Slump test is widely used to check the workability of concrete in laboratories and on site too.

Test Procedure: The mould and base plate must be dampened first before adding any concrete. The mould must be held firm against the base plate while filling concrete in it.

The filling process consists of three layers. Each layer is compacted via stroking it with a tamping rod. The strokes must be distributed uniformly throughout the cross-section of each layer. Stroking must be done such that the rod donot touch the base plate. Every additional layer is penetrated with the rod to the top of the previous layer.

After the filling is completed, remove the spilled concrete from base plate and cut the surface of slump-cone with a ruler to get a straight-shaped face.

The lifting of mould needs serious attention. There must not be any torsional or lateral motions imparted to the concrete.

Test Results: Only true slump is taken into the account in case of ordinary concrete. In SFRC, it was noted that shear slump often occurs due to the greater stiffness and slight error in rod tamping.

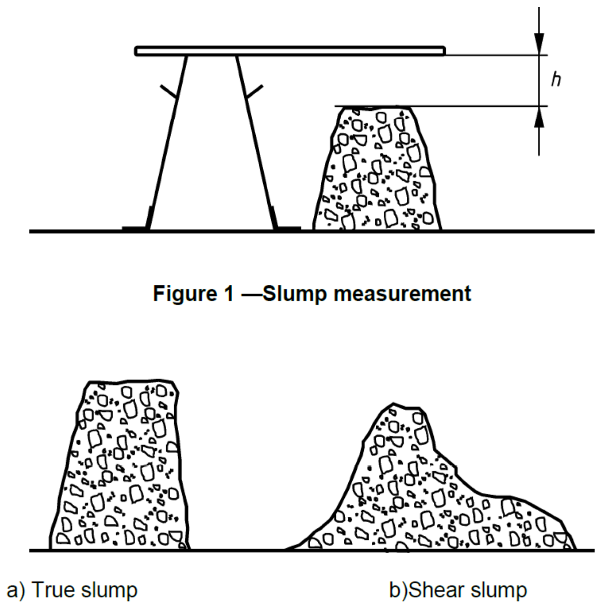

Figure 51: Form of slumps

'h' represents the value of slump in millimeters. Table 11 shows the different ranges of slump used.

Table 11: European Slump classes

Slump class	Slump Value (mm)
S1	10-40
S2	50-90
S3	100-150
S4	160-210
S5	≥ 220

The target slump class of this research is S3. The workability of SFRC is purely managed with altering SP percentage. SFRC is a stiffer material and needs an excess of SP content. Water content was kept constant throughout. Workability was adjusted according to S3 slump class for each of the four different steel fiber dosages.

Figure 52: Slump test

Following are the accepted mixes with S3 slump class.

Table 12: Slump values of mixes

Steel fiber dosage *(kg/m³)*	Super plasticizer *(%)*	Slump value *(mm)*
35	0.4	145
50	0.6	140
75	0,7	140
100	0.85	135

4.5.2 Hardened concrete tests:

Only compression and flexure tests were included at preliminary stage. While the final tests included compression, flexure, impact and shear tests. Following are the description of tests performed.

4.5.2.1 Residual Flexural tensile strength ($f_{R,i}$) (SFS-EN 14651)

Principle: Three-point bending test is conducted and ultimate load capacity is measured against CMOD 0.5, 2.5, 3.5 mm.

- **Apparatus:**

1. Saw with rotating carborundum with adjustable and fixable cutting depth and 90^0 direction of saw-cut to the specimen lengths for notching the test specimen.
2. Callipe with an accuracy of 1mm.
3. Rule with reading capability of 1mm.
4. Testing machine meeting class-1 requirements in EN 12390-4.
5. Device for transmitting the load of the testing machine to the test specimen, made up of two supporting rollers and one loading roller.
6. Load measuring device capable of measuring loads to an accuracy of 0.1 kN.
7. Linear displacement transducer capable of measuring displaceemnts to an accuracy of 0.01mm.
8. Device (frame) for mounting displacement transducer.
9. Data recording system coupled directly to electronic outputs of load and CMOD or deflection with a recording rate not less than 5 Hz.

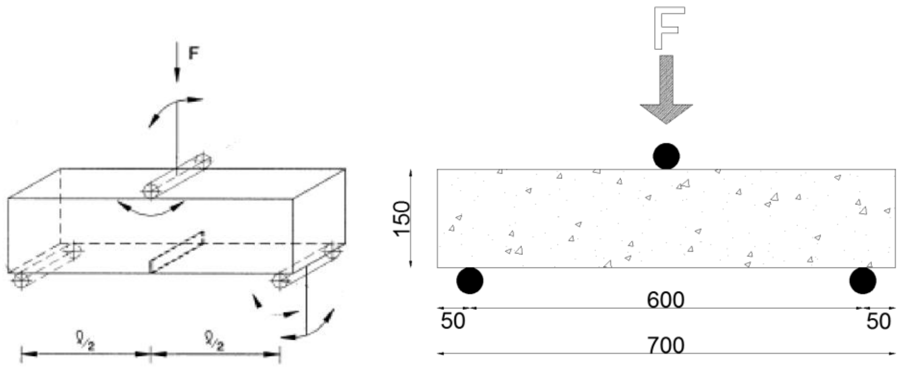

Figure 53: SFS-EN 14651 apparatus

- **Specimen preparation:**

1. **Shape and size of test specimen**

The test specimen shall be prisms conforming to EN 12390-1 with a nominal width and depth of 150mm and a length of 550 mm ≤ L ≤ 700 mm.

2. **Manufacture and curing**

The procedure for filling the mould is indicated in Figure 54; the mould shall be filled up to approximately 90% of the height before compaction. The compactor used must be exterior or table compactor.

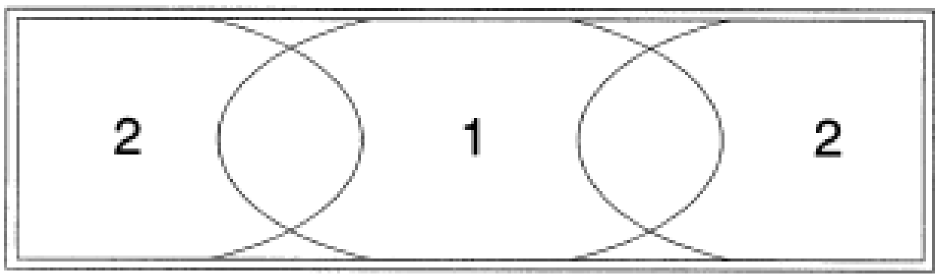

Figure 54: Procedure for filling the mould

3. **Notching the test specimen**

Wet sawing shall be used to notch the test specimen. Specimen shall be rotated over 90^0 around their longitudinal axis and then sawn through the width of specimen at mid-span.

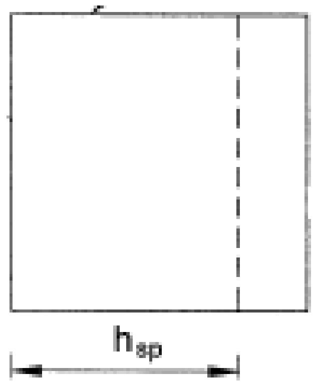

Figure 55: Position of the notch sawn into the test specimen

Where,

h_{sp} Must be 125 $\pm$ 1mm

- **Test Procedure:**

The beam specimen shall be balanced on wiped and cleaned rollers according to Figure 56; balanced on either side. The procedure of finding CMOD and displacements are different but either of one can be changed into the other. In case of CMOD, the machine shall be operated so that CMOD increases at a constant rate of 0.05 mm/min. When CMOD = 0.1 mm, the machine shall be operated so that CMOD increases at a constant rate of 0.2 mm/min. The test shall not be terminated before CMOD reaches 4 mm.

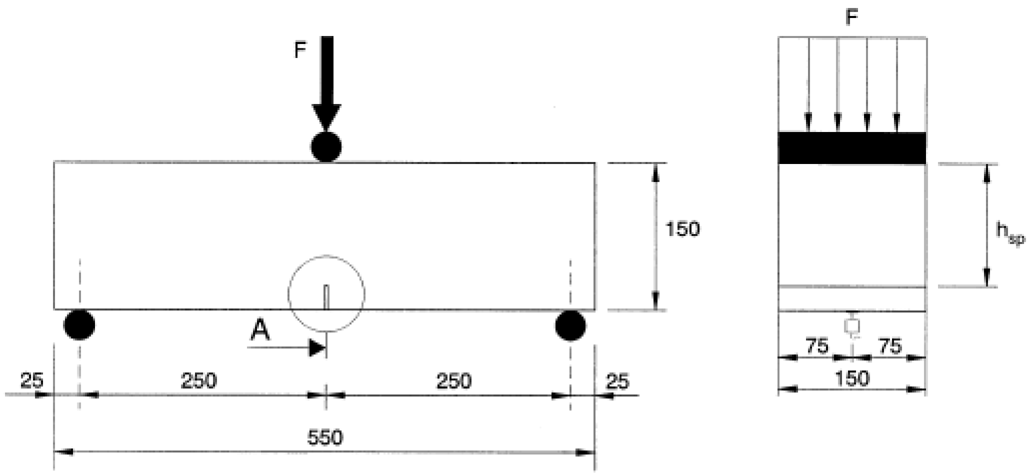

Figure 56: Typical arrangement of EN 14651

➢ **Results:**

1. **Equivalence between CMOD and deflection**

The relation between CMOD and deflection may be approximated as;

$$\delta = 0.85\ \text{CMOD} + 0.04$$

Where,

δ Deflection in mm

2. **Residual flexural tensile strength**

The residual flexural tensile strength $f_{R,i}$ is given by the expression;

$$f_{R,i} = \frac{3*F*l}{(2*b*hsp^2)}$$

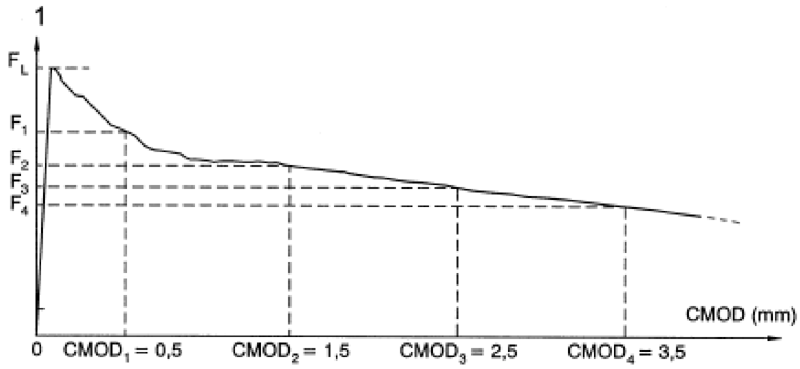

Figure 57: Load-CMOD diagram and F values

4.5.2.2 Compressive Test of Concrete (EN 12390-3):

Principle: Concrete sample are loaded to the compression machine confirming EN 12390-3. Result is taken as the maximum load resisted by a specimen.

Apparatus: Compression testing machine

Specimen preparation: For such a test, three cubical sample is needed for every concrete composition having 100x100x100mm^3 dimensions. The moulds must be covered with plastic sheets after being filled with concrete. Demoulding happens after 24 hours leading to curing of specimen. Usually specimens are kept under water for a better hydration. The compression strengths are evaluated on 7th and 28th day of concrete mix. Multiple cubes are casted depending upon the different mixes designed. Average strength of each age group is taken as the compressive strength.

Procedure: The bearing plate must firstly be cleaned leading to the removal of excessive moisture from the surface of cubical concrete samples. Cubes must be set accurately with respect to lower plate to an accuracy of 1% of cube size. Loading rate is of greater importance and must be set according to the standard i.e. 0.6 N/mm^2. The cubical samples are loaded till failure occurs and the strength is noted down. Multiple samples against a same concrete sample are tested and the average strength is finalized to be the compressive strength of such concrete mix.

4.5.2.3 Five-point bending test of slabs

Principle: CMOD and deflection is checked, till the failure is reached, against five-point bending.

- **Apparatus:**

1. Two jacks with a loading capacity exceeding the failure capacity of slabs.
2. Deflection measuring devices.
3. CMOD measuring devices.
4. Testing machine meeting class-1 requirements in EN 12390-4.
5. Device for transmitting the load of the testing machine to the test specimen, made up of three supporting rollers and two loading roller.
6. Load measuring device capable of measuring loads to an accuracy of 0.1 kN.

- **Specimen preparation:**

1. **Shape and size:**

The length of all four slabs, to be tested, is kept 5000mm. Besides, width is variable, depending on the strength requirements.

2. **Manufacturing and Curing:**

SFS-EN 12390-2 is followed for the manufacturing and curing purpose. All four slabs were casted at Rudus Oy concrete plant.

Test slabs are of the following types;

- **Slab-1:** Conventionally reinforced slab with plain concrete
- **Slab-2:** SFRC slab with steel fiber dosage-35 kg/m^3.
- **Slab-3:** SFRC slab with steel fiber dosage-50 kg/m^3.
- **Slab-4:** SFRC slab with steel fiber dosage-35 kg/m^3 and conventional reinforcements.

- **Test procedure:**

The slab specimen shall be balanced on wiped and cleaned rollers according to balanced on either side. Load must not be applied until all loading and supporting rollers are resting evenly against the test specimen. Loading is set to be deflection controlled with a rate of 0.4mm/min. Record the deflection and CMOD against the loading. Note down the optimum load resisted by the slab.

3. **Slab test schedule:**

Every test should run till the collapse of slab occurs. Keeping the laboratory limitations in context, slabs are designed to fail before the load reaches its optimum capacity (500 kN/jack). The loading capacity may differ by small margin as it is not possible to test all four slabs on its 28th day strength but the variation will be negligible.

Following is the pattern of tests.

- **Slab Test – 1:** SFRC-35
- **Slab Test – 2:** SFRC-50
- **Slab Test – 3:** Reinforced slab
- **Slab Test – 4:** Reinforced + SFRC-35

4.5.3 Slab Capacities:

As stated above, four different slab specimen shall be tested, each with different steel fiber dosage.

First two slabs are purely steel fiber reinforced slabs. The moment capacity is calculated forehand according to the design guide BY-66. The first specimen in Table 13 stating *Test slab (BY-66)* is the design check of a slab provided as an example in BY-66 to assure that the calculations made are correct.

Third slab is conventionally reinforced with no steel fibers. This slab is taken as a bench mark for the last slab. Combination slab states the combination of conventional and steel fiber slab and will be compared to the third slab. Keeping the conventional reinforcement same will allow us to compare adequately the positive features added by steel fibers.

Following are the designed and test moment capacities and required line force for falure of individual slab specimen.

Table 13: Slab capacities

Description	Slab Depth	Slab Width	Moment Capacity		Force	
			Design	Test	Design	Test
	mm	*mm*	*kN-m*	*kN-m*	*kN*	*kN*
Test Slab (BY-66)	280	1000	56,9		91	
SFRC-35	220	1200	51	76	68	102
SFRC-50	220	1200	62	93	82	124
CRS	200	1200		94		150
CRS + SFRC-35	200	1200	101	133	134	177

*All dimensions are in millimeters.

*Test Slab (BY-66) is a sample slab designed to cross-check calculations according to the mentioned design guide.

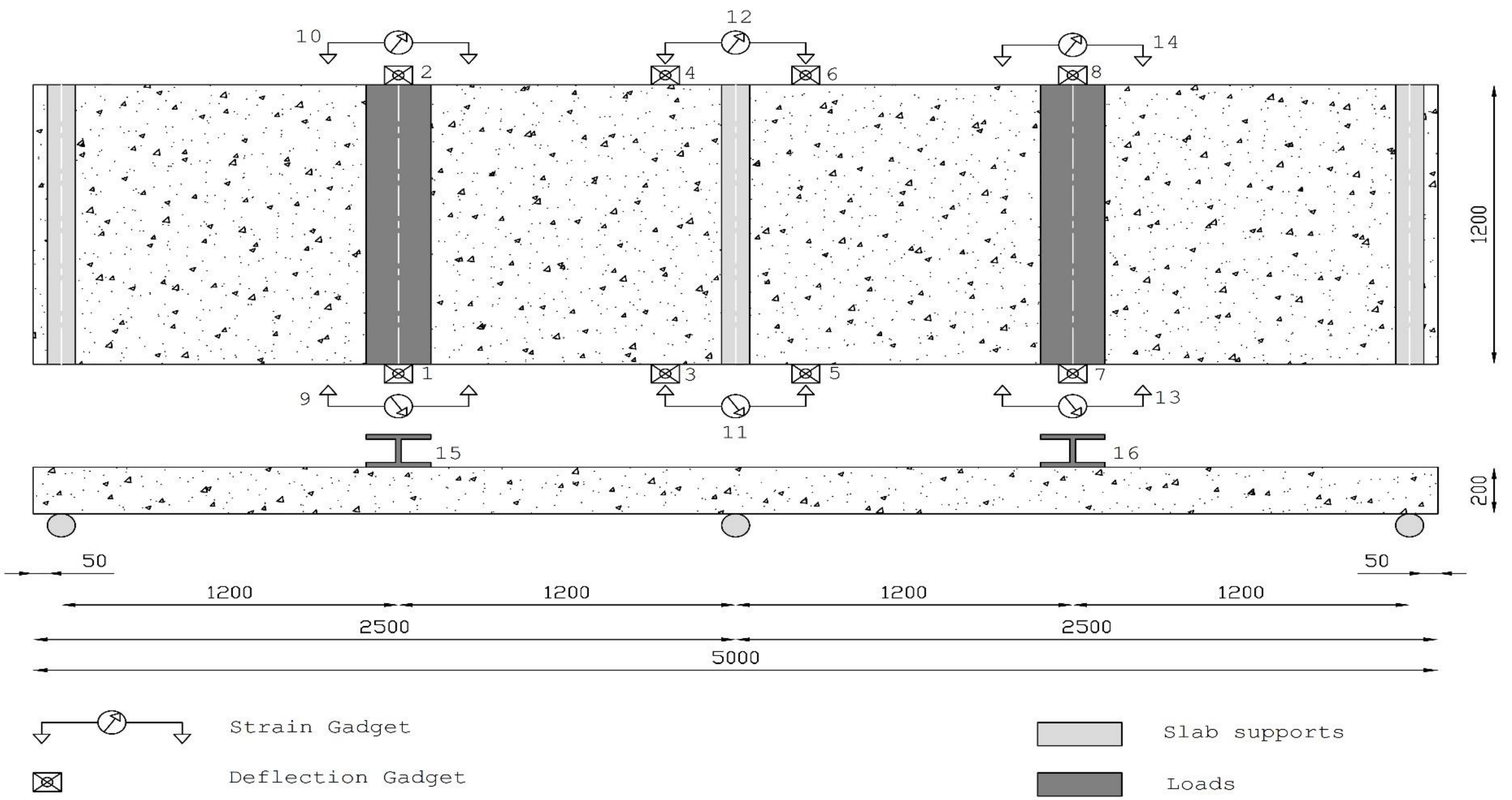

Figure 58: Slab test setup

Figure 59: Slab test setup

CHAPTER 5 : TEST RESULTS AND CONCLUSION

5.1 Compressive tests (EN 12390-3):

The target concrete strength class is C35/45. Cubes were casted to check the compressive tests and assure that the mix design is producing targeted strength. Cubes were casted for plain concrete. There was no steel fibers introduced to concrete at this stage.

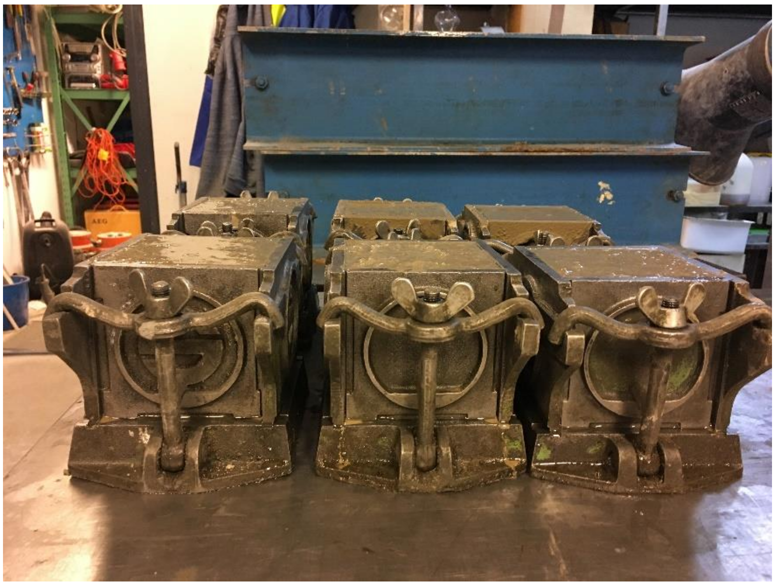

Figure 60: Concrete cube specimen

From Figure 61, steel fibers enhance compressibility of concrete. The increasive gradient of compressive strength directly depends on steel fiber dosage.

A parabolic equation is derived using available data to predict the compressive strength enhancement of SFRC specimen. Besides, our data set is not sufficient and a major data set is require to get a precise equation with which we can accurately calculate compressive strength enhancement due to the inclusion of steel fibers.

Compressive strength plays vital role while designing different structural members. Especially, the structure members resting on ground or having area support. This unique advantage of SFRC can be utilized in designing grad-slabs and pile slabs.

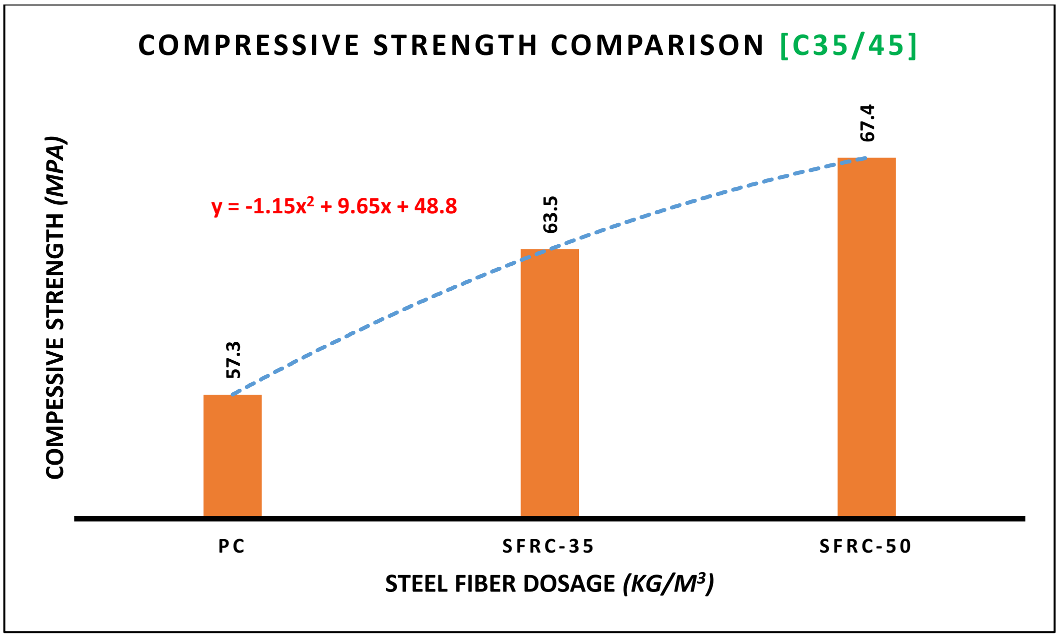

Figure 61: Compressive strength enhancement using steel fibers

Following is the compression test results of C35/45 without steel fibers.

Table 14: Compressive test results

S.No	ID	Specimen dimensions			Mass	Raw Density	Compressive strength
		Length	Width	Depth			
		mm	*mm*	*mm*	*kg*	*kN/m³*	*MPa*
1	SFRC-C/1	99	99	100	2,38	24,3	49,5
2	SFRC-C/2	99,7	99,7	99,8	2,39	24,1	50,3
3	SFRC-C/3	100	100	99,7	2,38	24,0	48,4
4	SFRC-C/4	99,9	99,9	100	2,38	23,9	50,4
5	SFRC-C/5	99,5	99,5	100,7	2,44	24,5	52,4
6	SFRC-C/6	100	100	99,8	2,37	23,8	48,5
Mean Compressive strength							**49,9**
Standard deviation							**1,5**

Furthermore, concrete cylinders were casted to take, if there, any effect of steel fibers on the compressibility of concrete.

5.2 Beam test results

SFS-EN-14651 beam tests were performed to get residual flexural tensile strengths of induced steel fiber dosages. Six samples were tested against each steel fiber dosage. The mix ID used are presented below;

- SFRC-B-35 (C35/45 concrete beam with 35kg/m³ of steel fibers)
- SFRC-B-50 (C35/45 concrete beam with 50kg/m³ of steel fibers)
- SFRC-B-75 (C35/45 concrete beam with 75kg/m³ of steel fibers)
- SFRC-B-100 (C35/45 concrete beam with 100kg/m³ of steel fibers)

Following are major steps towards testing.

5.2.1 Three-point bending tests:

The test setup used is three-point bending. Transducer detected crack mouth opening displacement (CMOD). The setup was according to SFS-EN-14651 mentioned in 4.5.2.1

Figure 62: 3-point beam bending test setup

Individual results against every beam specimen with particular steel fiber dosage are mentioned in the following passage.

5.2.1.1 SFRC-B-35

Steel fibers act as reinforcement providing a much smoother and linear curve to concrete as shown in the Figure 63. Concrete beam loses strength after it pass its tensile strength capacity and the curve gets elevated as the steel fibers are activated till it reaches its ultimate strength. The dropping down of curve is linear rather an exponential fall as the specimen losses its strength. Following table shows the important perimeters.

Table 15: Perimeters of SFRC-B-35/1-7

ID	Maximum Load F_L	Load at CMOD		
		$F_{0.5}$	$F_{2.5}$	$F_{3.5}$
	kN	*kN*	*kN*	*kN*
SFRC-B-35/1	23,8	20,2	22,1	17,9
SFRC-B-35/2	19,8	17,7	14,8	12,6
SFRC-B-35/3	17,4	16,2	15,0	11,4
SFRC-B-35/4	17,8	15,0	16,8	13,6
SFRC-B-35/5	22,1	20,6	17,4	14,8
SFRC-B-35/6	20,4	18,4	17,1	15,1
SFRC-B-35/7	19,1	16,8	15,6	13,5
Mean strengths	**20,1**	**17,8**	**16,94**	**14,13**
Standard deviation	**2,3**	**2,0**	**2,5**	**2,1**

The results obtained according to above mentioned test standard for SFRC-B-35 are mentioned in the following;

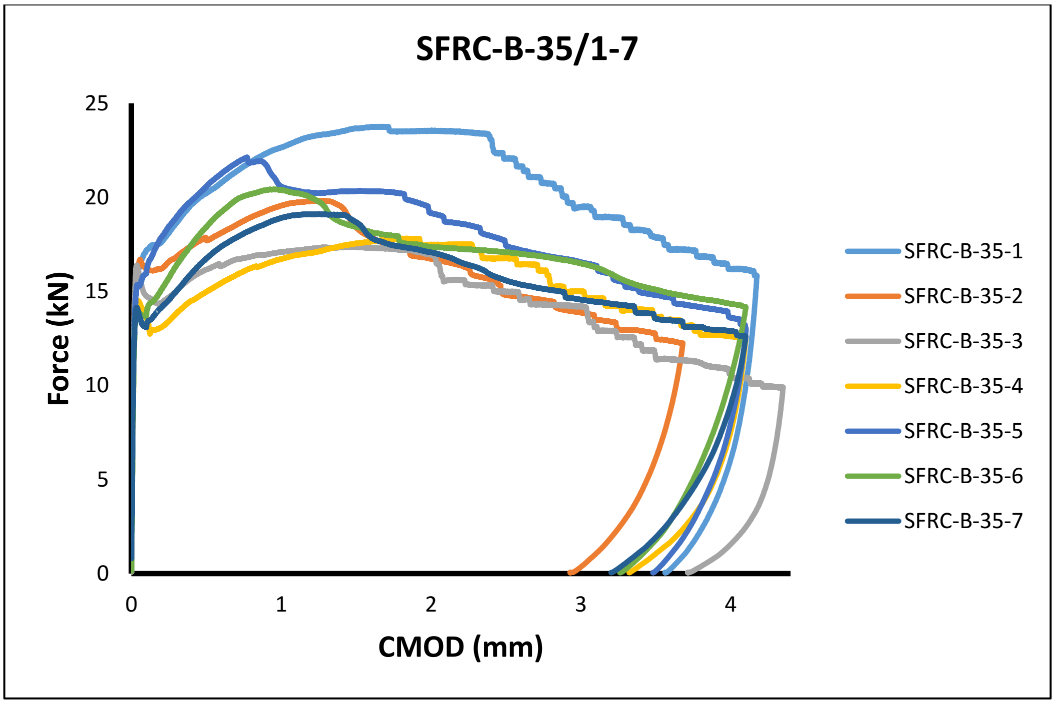

Figure 63: Test results of SFRC-B-35/1-7

5.2.1.2 SFRC-B-50

A slight enhancement of load bearing can be noticed with a small enhancement of steel fiber dosage. Following table shows the mechanical strengths obtained.

Table 16: Perimeters of SFRC-B-50/1-6

ID	Maximum Load F_L	Residual strengths		
		$F_{0.5}$	$F_{2.5}$	$F_{3.5}$
	kN	*kN*	*kN*	*kN*
SFRC-B-50/1	22,2	20,0	21,2	17,3
SFRC-B-50/2	26,0	22,4	24,7	18,7
SFRC-B-50/3	23,5	21,6	21,2	17,7
SFRC-B-50/4	24,6	21,6	19,8	16,3
SFRC-B-50/5	20,9	19,2	19,6	17,9
SFRC-B-50/6	27,8	23,6	22,1	19,6
Mean strengths	**24,1**	**21,4**	**21,4**	**17,9**
Standard deviation	**2,5**	**1,6**	**1,9**	**1,1**

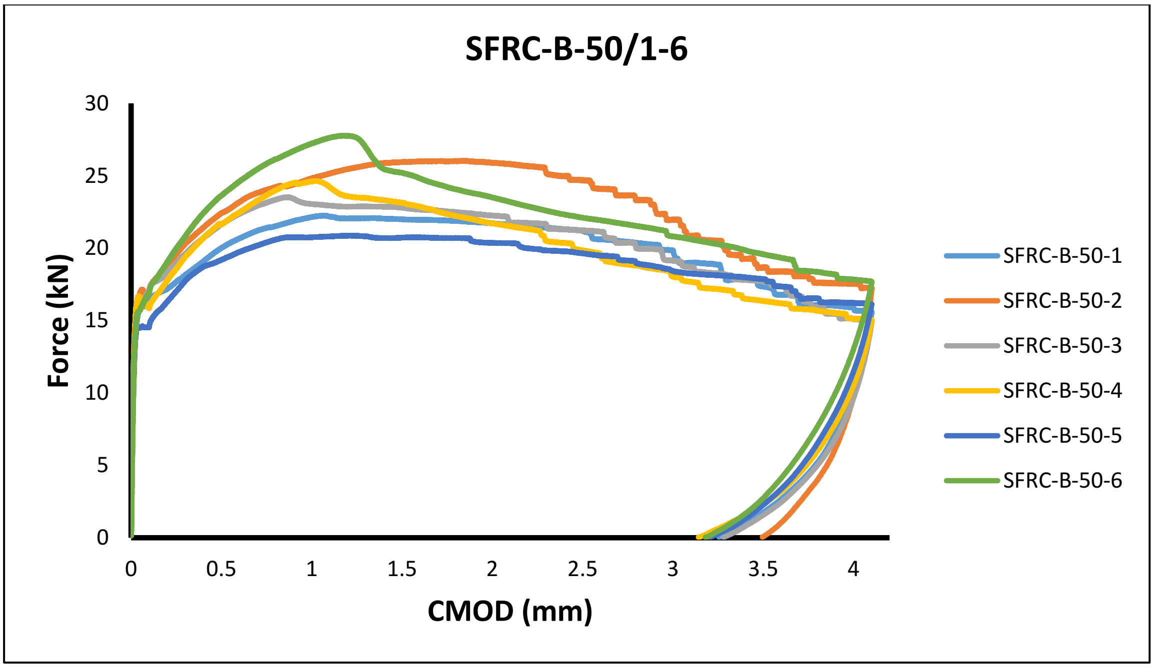

Figure 64: Test results of SFRC-B-50/1-6

The results obtained according to test standard for SFRC-B-50 are mentioned in Figure 64.

5.2.1.3 SFRC-B-75

Introduction of high steel fiber dosage brings significant changes to the behavior and can be noticed in Figure 65. The dropping of curve when the concrete losses its tensile strength is negligible and steel fibers takes the load simultaneously.

As the mix is dense with steel fibers, leading to a high strength resistance. The curve leads to ultimate load with a higher slope and enhanced results. Furthermore, dropping of curve is smooth and linear. Unlike the other specimens mentioned before, SFRC-B-75/1-6 is resisting the loads more significantly and its plot is laying in strain hardening. The slope of the curve drop is signigicantly reduced leading to a more stable composite material.

The difference of resisting loads at different CMOD is paltry. This behavior translates that using such material for structural purposes is more stable and mitigative.

Following table shows important design perimeters of SFRC-B-75.

Table 17: Perimeters of SFRC-B-75/1-6

ID	Maximum Load F_L	Residual strengths		
		$F_{0.5}$	$F_{2.5}$	$F_{3.5}$
	kN	*kN*	*kN*	*kN*
SFRC-B-75/1	28,5	27,2	25,5	23,1
SFRC-B-75/2	27,4	26,1	25,6	24,1
SFRC-B-75/3	24,2	23,2	21,6	19,6
SFRC-B-75/4	25,0	23,0	22,2	19,6
SFRC-B-75/5	30,7	30,6	27,1	25,2
SFRC-B-75/6	29,4	27,3	21,8	20,7
Mean strengths	**27,5**	**26,2**	**24,0**	**22,1**
Standard deviation	**2,5**	**2,9**	**2,3**	**2,4**

Figure 65 provides a pictorial overview of SFRC-B-75/1-6 behavior. Six samples were tested and results are mentioned for each under separate colors.

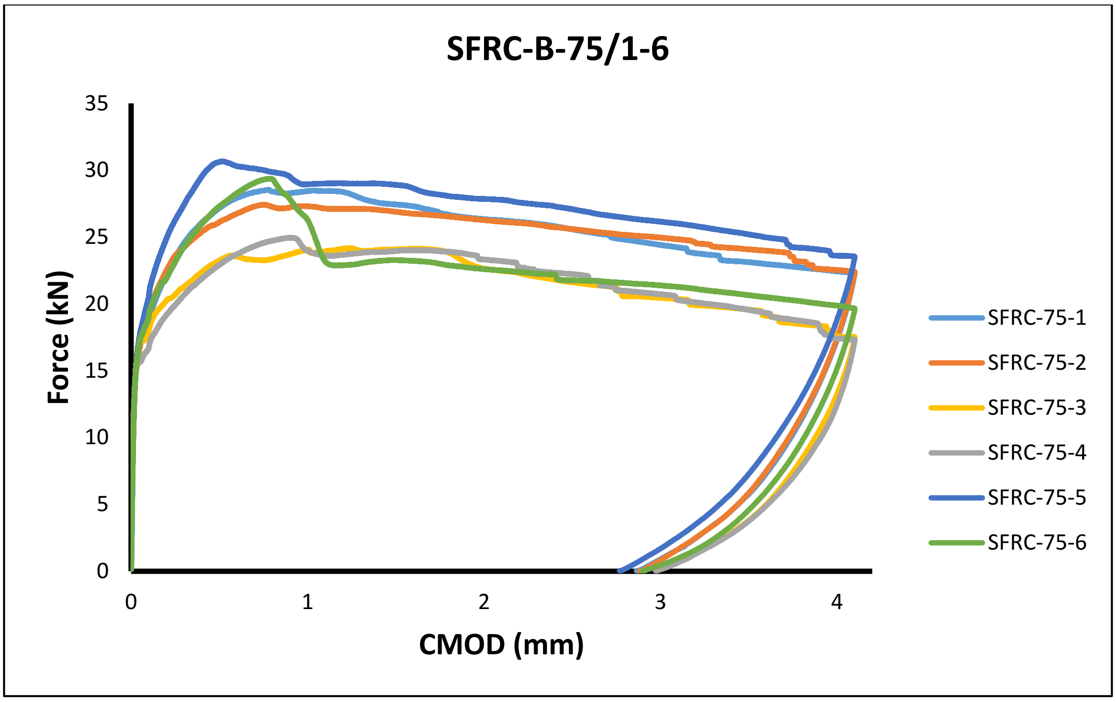

Figure 65: Test results of SFRC-B-75/1-6

5.2.1.4 SFRC-B-100

Addition of steel fibers adds mechanical strength to concrete till a point when the density of steel fibers gets so high that there is not enough concrete matrix to hold it.

SFRC-B-100 is considerably a high dose and brings fatigue in mixing and casting. Besides, it brings positive features by adding tensile strengths. Like SFRC-B-75, this specimen also transferred the load to steel fibers instantaneously when concrete lost its tensile strength.

Difference of load resistence on different CMODs is negligible. Load resistance is maintained till 4.1mm CMOD. This concrete mix is much safer compared to the last three specimens.

Following table shows the strength perimeters at differential CMODs.

Table 18: Perimeters of SFRC-B-100/1-6

ID	Maximum Load F_L	Residual strengths		
		$F_{0.5}$	$F_{2.5}$	$F_{3.5}$
	kN	*kN*	*kN*	*kN*
SFRC-B-100/1	34,0	31,1	31,4	29,1
SFRC-B-100/2	30,3	29,6	28,1	26,0
SFRC-B-100/3	32,1	30,5	27,9	26,2
SFRC-B-100/4	32,2	30,5	29,0	26,2
SFRC-B-100/5	39,4	35,1	38,8	36,9
SFRC-B-100/6	38,2	35,6	35,5	28,6
Mean strengths	**34,4**	**32,1**	**31,8**	**28,8**
Standard deviation	**3,7**	**2,6**	**4,5**	**4,2**

Following figure illustrates the behavior of SFRC-B-100/1-6;

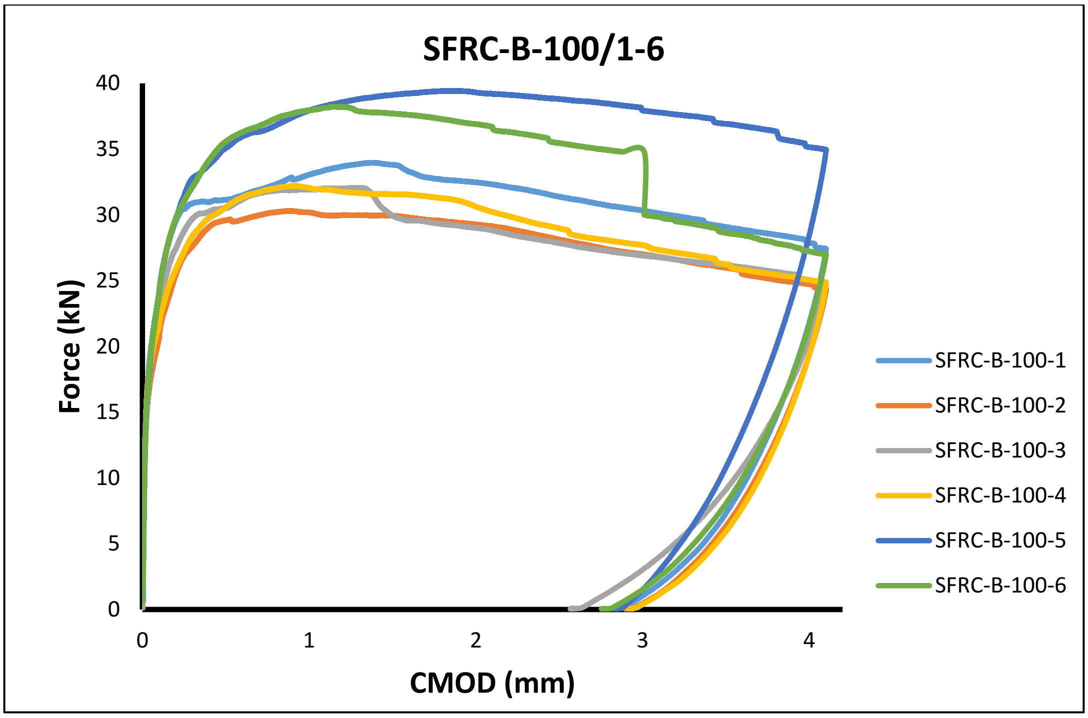

Figure 66: Test results of SFRC-B-100/1-6

5.2.2 Standard deviation of Beam test

Standard deviation plays an important role when it comes to the authenticity of results. Lesser deviationis are preferred and shows accurate results. Moreover, standard deviation tells if the results are precise enough to be considered.

Above mentioned table shows standard deviation locally of every beam test class with differential steel fibers used. This section takes a global analysis of standard deviation to have a clear vision.

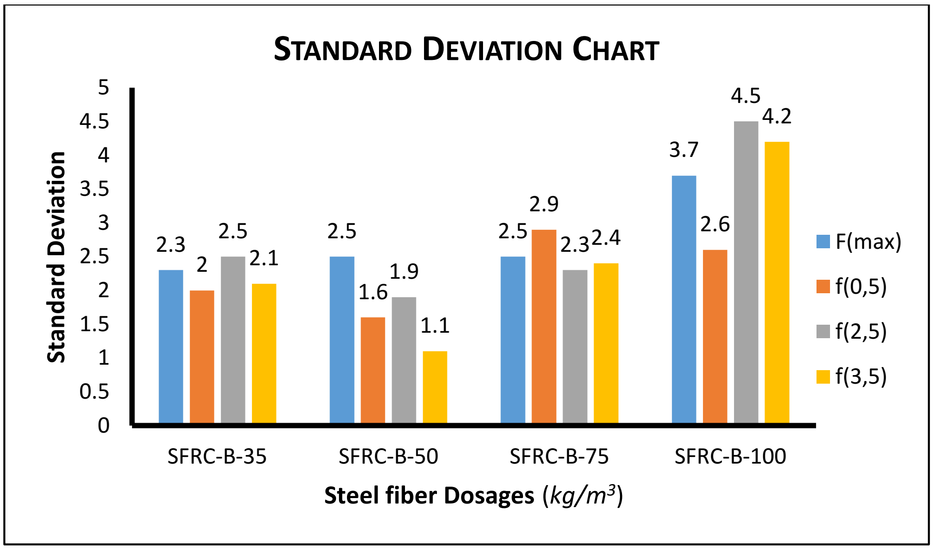

Figure 67: Standard deviation chart

It is clear from Figure 67 that the deviation is increasing with increasing steel fiber dosage and vice versa. The most important entity are *f(0.5)* and *f(2.5)*. in the chart, "f" shows the load in kN while "( )" shows the CMOD in millimeters. So ***f(0.5)*** means the load at 0.5mm CMOD.

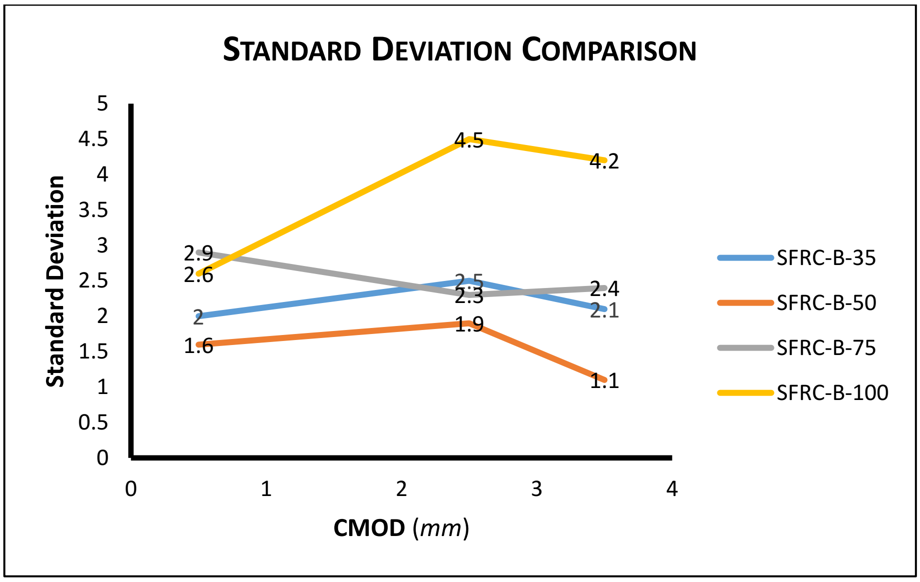

Figure 68: Standard deviation comparison

Figure 68 compares the standard deviation of steel fiber dosages used. Moreover, the above mentioned chart provides a more clear view of the standard deviations. Only the design entities are taken into context and the maximum load taken by every sample is neglected in this case.

Figure 68 also shows that standard deviation increases with increasing steel fiber dosage and vice versa. It is clear from the above mentioned chart that SFRC-50 shows the least standard deviation.

5.3 Comparison of beam tests

Four different steel fiber dosages were used in this research project. Six beams were tested for every steel fiber class to get design residual flexural tensile values. An average of every steel fiber class is drawn to compare the strength enhacement with differential steel fiber dosage.

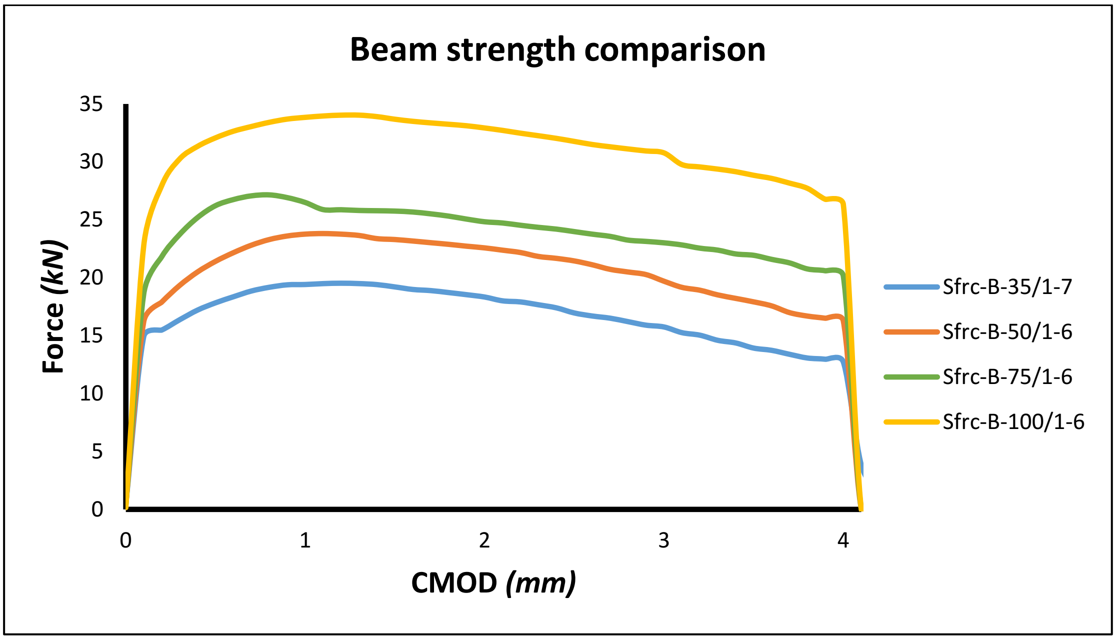

Figure 69: Comparison of beam specimen with differential steel fiber dosages

As steel fiber dosage is increased, an increasive strength behavior is shown as stated in Figure 69. Moreover, steel fibers have taken the load instantaneously, with increased steel fiber dosage, when concrete loses its very own tensile strength. When concrete loses its tensile strength, a crack is formed which is likely to be promoted to a major crack if there is lacking any resisting material. In our case, steel fibers are acting as crack arrestors, restricting the formation of crack and absorbing stresses.

Concrete, without steel fibers, shows strain softening phenomenon after losing tensile strength and the crack produced propagates to major crack resulting in a brittle failure. Besides, with the addition of steel fibers, SFRC shows strain hardening at an instant when concrete loses tensile strength. The scope of strain hardening is directly dependent upon steel fiber dosage. Denser the concrete mix is of steel fibers, more strain hardening is resulted.

Moreover, Figure 70 also shows us whether the resulted behavior is retaining yielding strength or bending hardening. Lesser steel fiber dosages can also result in bending softening if there is not enough fibers to retain the loading rate. But still, even with a lesser denser dose, the inclusion of steel fibers omits brittle failure.

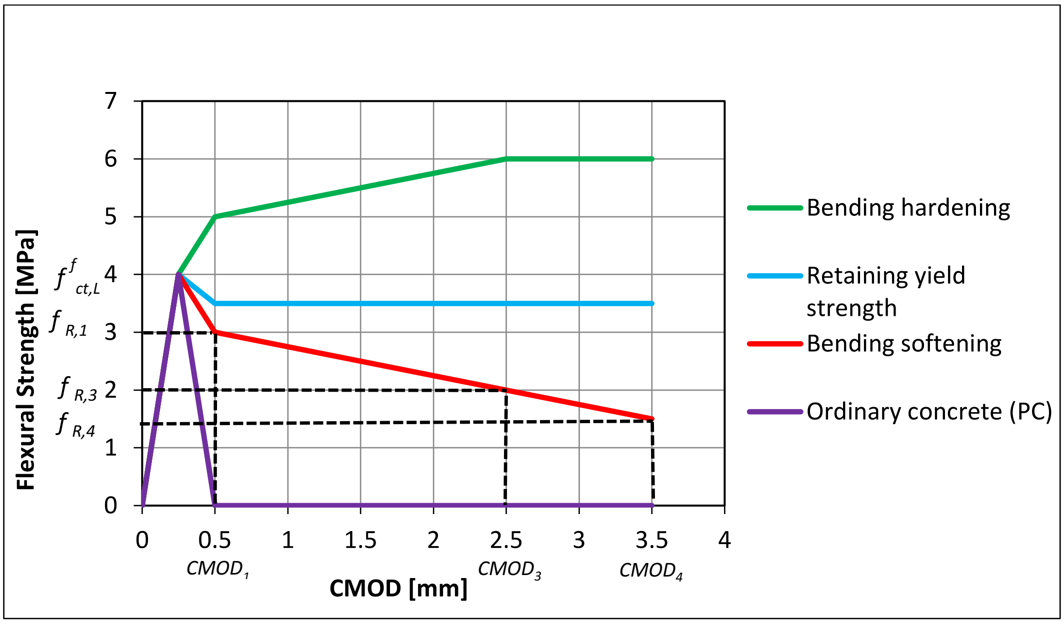

Figure 70: Schematic behaviour from beam testing in accordance to SS-EN 14651

Besides, Figure 71 discusses the behavior of differential steel fiber dosage. It is clear from the figure, shown below, that the increasive order of steel fibers promote bending hardening. SFRC-B-35/1-6 shows retaining yield strength behavior with a slight bending hardening phenomenon. While denser dosages clearly leaps to bending hardening and retains a ductile nature.

The drop after touching peak load is not significant in all SFRC beam cases. Besides, all the specimen showed a stable nature with gradual failure.

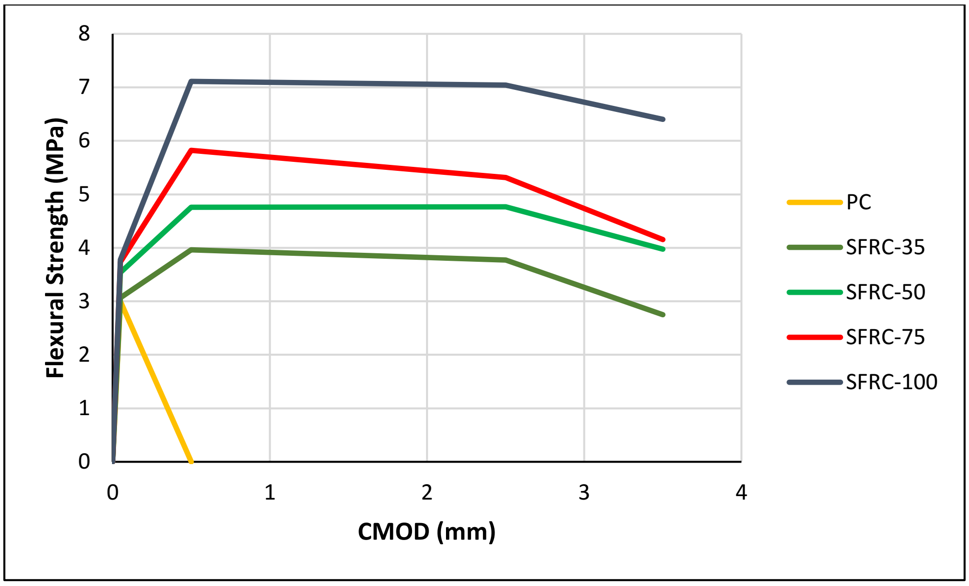

Figure 71: Strain hardening of SFRC

Moreover, it is required of every structural composite material to show strain hardening in order to be considered safe. The beam tests performed showed that SFRC results in a ductile failure rather a brittle which make it sound and reliable. Modern technology is evolving design techniques to introduce SFRC to construction industry as a major structural composite material.

5.4 Slab test results

Four slabs were casted and cured at Rudus concrete plant. Perimeters of slabs are provided in Figure 58. Moreover, the testing setup was set to be deflection controlled and the loading rate was set to be 0.4mm/min. Total of sixteen channels were used for every slab tests. Among these channels, eight channels for deflection and six channels for deformation values were planted. Besides, two channels were used to control the loading.

Following are the slab notations;

1. Slab-1: SFRC-35
2. Slab-2: SFRC-50
3. Slab-3: Conventionally reinforced slab (CRS)
4. Slab-4: CRS+SFRC-35

5.4.1 Slab-1: SFRC-35

Pure SFRC slab with steel fiber dosage of 35 kg/m^3. The design capacity was calculated prehand using BY-66 as a design guide. Moreover, the strength values were extracted from beam tests performed according to SFS-EN 14651 as mentioned earlier. Deflection and deformation were the prime targets. The following passage elaborates each feature in graphical form.

5.4.1.1 Deflection of SFRC-35

Deflection at two different points will be discussed. The points of deflection channels are mentioned in Figure 58.

Figure 72 shows the deflection at loaded span. It is clear from the graph that the deflection is resisted by steel fibers after concrete tensile strength is lost.

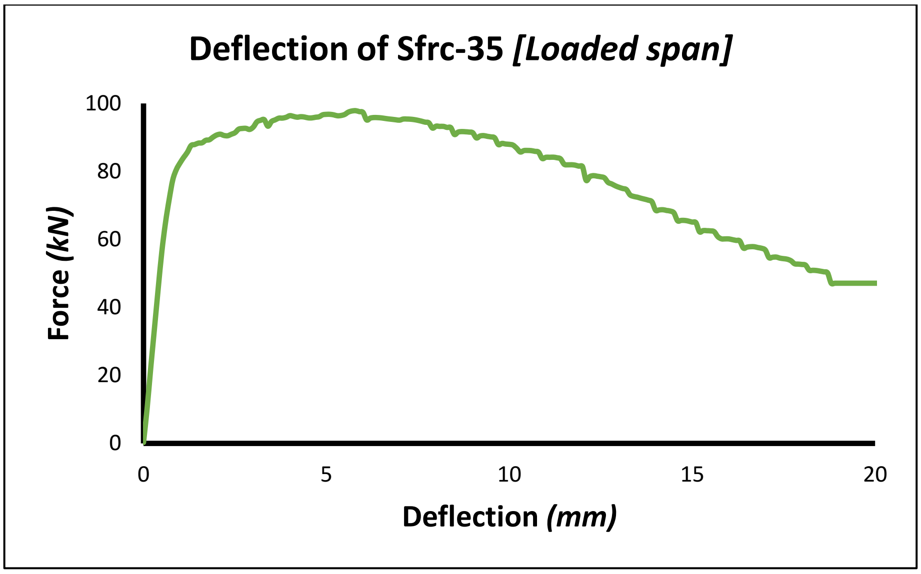

Figure 72: Deflection of SFRC-35 [Loaded span]

Figure 73 shows the deflection of SFRC-35 slab specimen at centre support. Likewise, deflection at centre also translates a linear failure with a small dropping gradient.

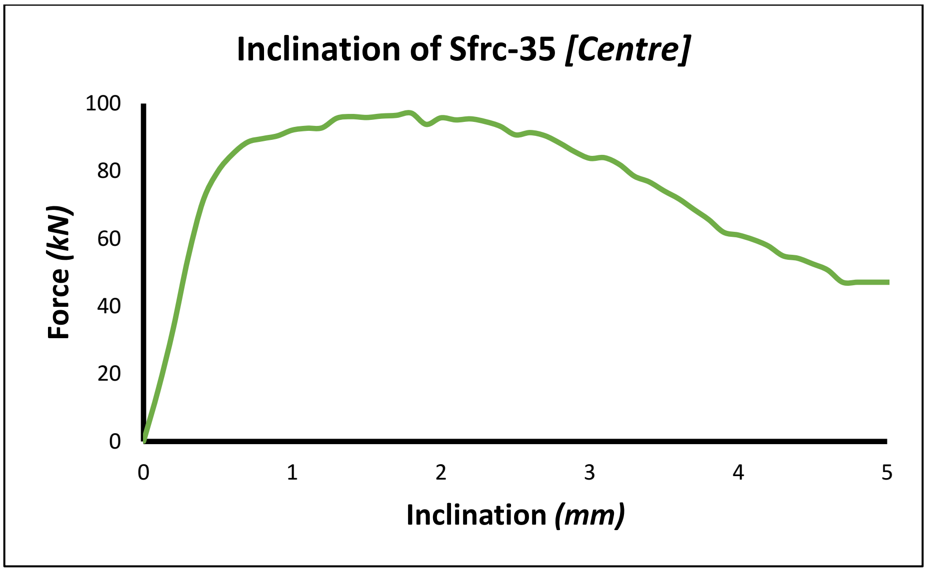

Figure 73: Inclination of SFRC-35 [Centre]

5.4.1.2 Deformation of SFRC-35

Deformation is measured at three different location and the data is polished according to the cracks which appeared right where expected.

Deformation is taken as crack mouth opening. Strain values can also be calculated from the data set but direct CMOD is preferred to have an elaborated view of results.

Deformation of SFRC-35 shows a stable gesture to loading. Furthermore, gradual drop is noted as the cross section cracks and the depth of concrete slab is reduced.

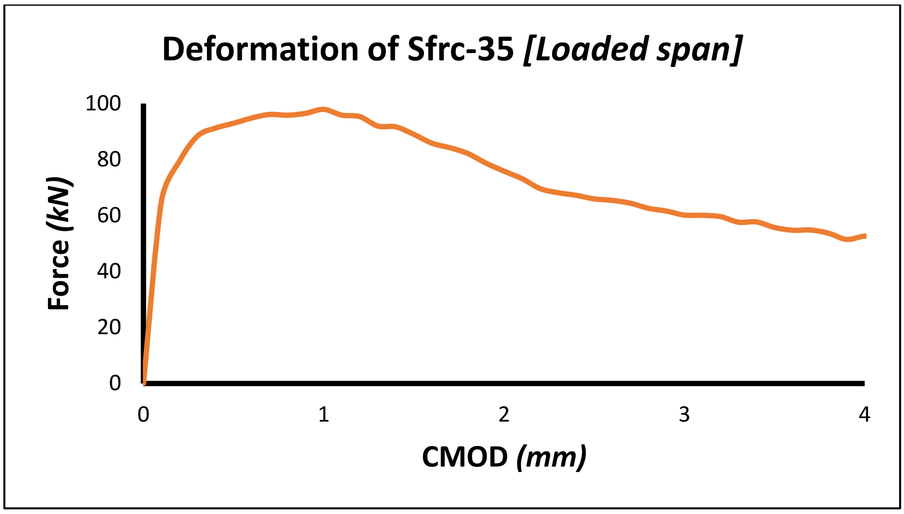

Figure 74: Deformation of SFRC-35 [Loaded span]

Figure 75 shows restrained behavior against loading. Steel fibers are continuously yielding as the cross-section is cracking. Moreover, reduced depth of cross-section have negligible effect on strength capacity and the slab is still taking approximately same load.

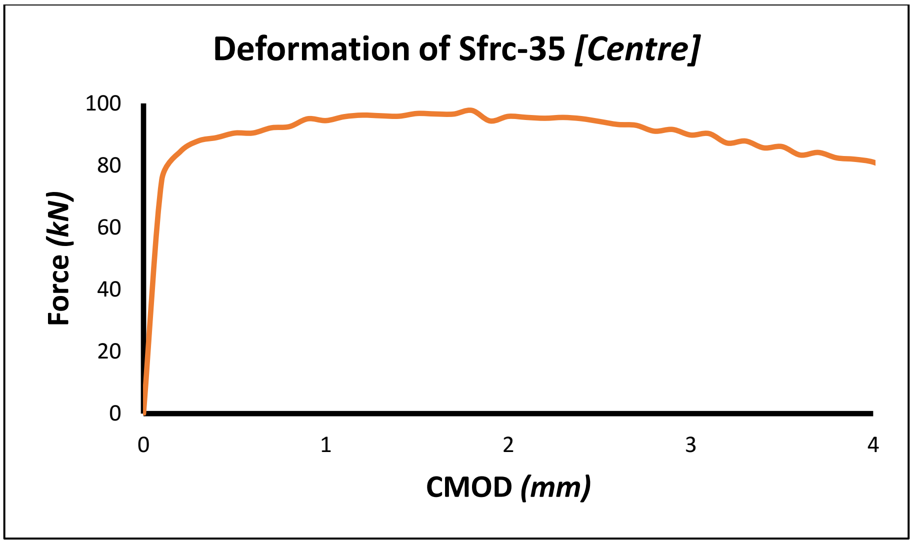

Figure 75: Deformation of SFRC-35 [centre]

5.4.2 Slab-2: SFRC-50

Pure SFRC slab with a steel fiber dosage of 50 kg/m^3. As mentioned in the previous case, deflection and deformation will be discussed in the following.

5.4.2.1 Deflection of SFRC-50

The location of deformation channels were kept same for all slab test specimen. Deflection is discussed through graphical representation at two different critical points.

Figure 76 shows the same linear behavior with a small dropping gradient with some extra resistance to deflection compared to SFRC-35 [Figure 72].

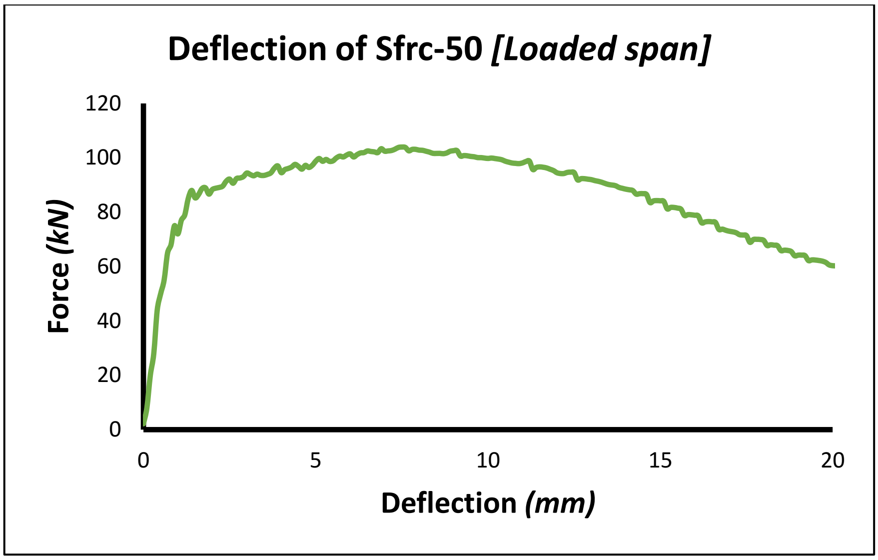

Figure 76: Deflection of SFRC-50 [Loaded span]

Centre support was considered critical. Some additional resistance was added in SFRC-50 slab specimen compared to SFRC-35.

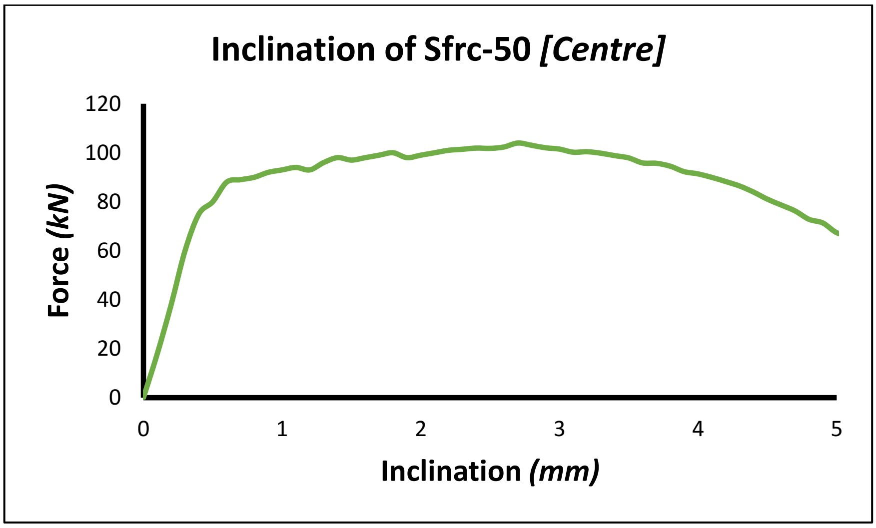

Figure 77: Inclination of SFRC-50 [Centre]

5.4.2.2 Deformation of SFRC-50

Deformation is taken as CMOD. Likewise, deformation will be elaborated in graphical format at two different critical points.

Increase in the amount of steel fibers result in increasing strengths and resistance against loading. It can be clearly seen from the graph provided if compared with Figure 74.

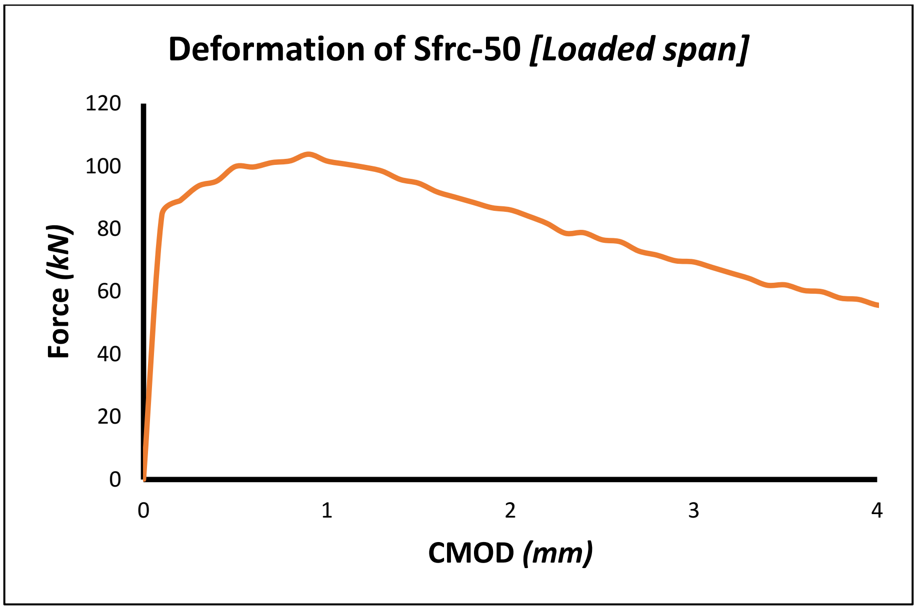

Figure 78: Deformation of SFRC-50 [Loaded span]

Centre point of the testing setup was considered critical as it was exposed to excessive negative moments. Deformation aat such point shows a linear behavior restraining the loads to a major crack level of 4mm.

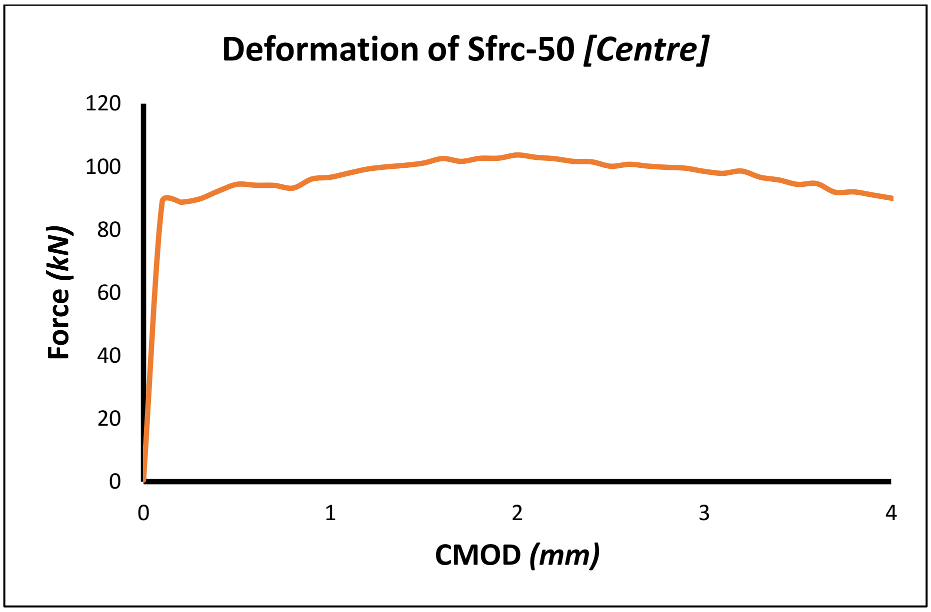

Figure 79: Deformation of SFRC-50 [Centre]

5.4.3 Slab-3: Conventionally reinforced slab (CRS)

A conventionally reinforced slab was also designed and casted. The purpose was to test another slab with the same reinforcement while replacing plain concrete with SFRC-35 and compare both.

5.4.3.1 Deflection of conventionally reinforced slab (CRS)

The testing setup and loading rate were kept same. All the channels were planted on the exact spots as planted on earlier slabs.

As concrete loses its tensile strength, conventional reinforcements are activated and start to take load. As ordinary rebars are flexible and ductile, allowing deflection at a controlled level.

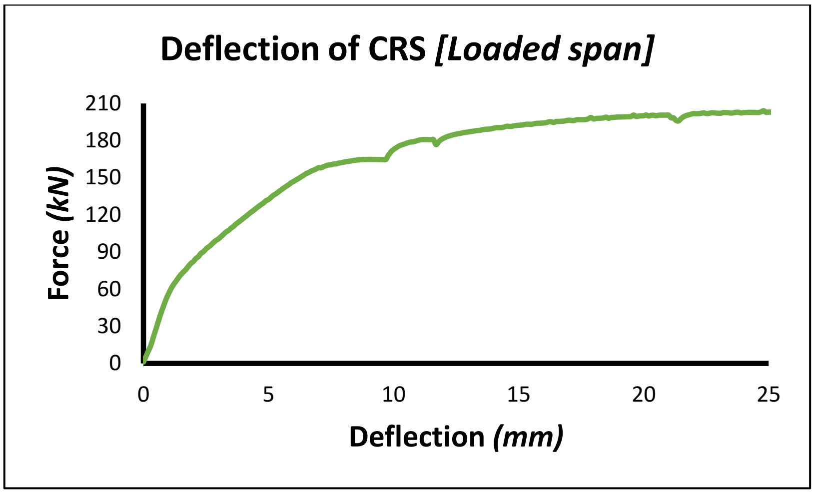

Figure 80: Deflection of CRS [loaded span]

Extra reinforcements were provided at centre point due to excessive negative moments. The drop is expected once rebars start yielding and the cross-section is reduced due to excessive cracks.

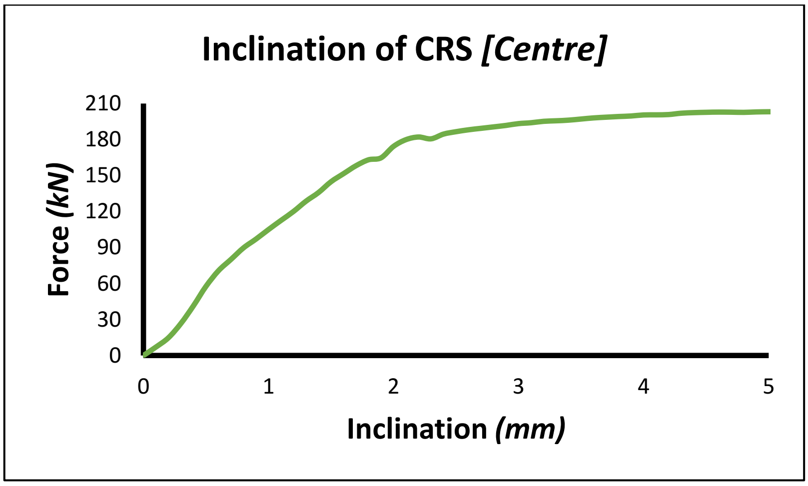

Figure 81: Inclination of CRS [Centre]

5.4.3.2 Deformation of conventionally reinforced slab (CRS)

Deformation is noted and discussed at two different critical points as did in earlier cases.

Crack appears instantaneously as the concrete loses its tensile strength. In case of conventionally reinforced slab, the load is then taken by rebar till it yield or fail.

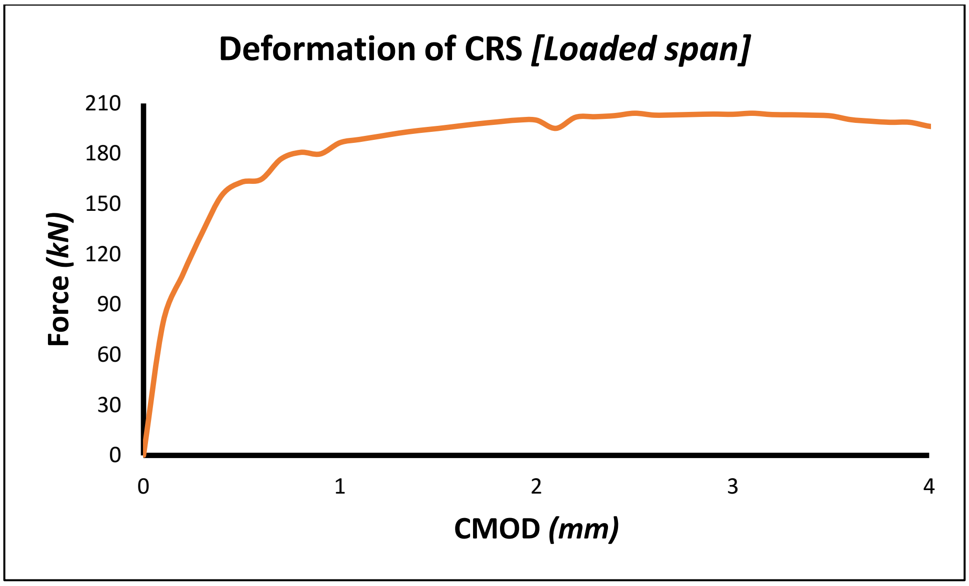

Figure 82: Deformation of CRS [Loaded span]

It is clear from Figure 83 that load is transferred to steel bars which causes an elevated load bearing, as shown in the graph. Furthermore, a ductile behavior is noted till the bar yield resulting in a collapse.

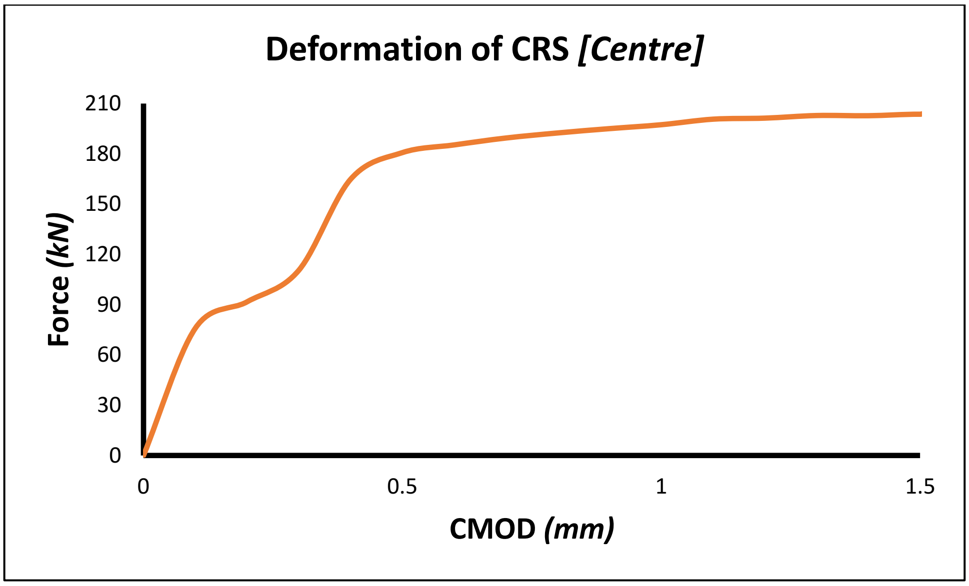

Figure 83: Deformation of CRS [Centre]

5.4.4 Slab-4: CRS+SFRC-35

This slab was designed and casted to compare it with Slab-3 which is only conventionally reinforced. Slab-4 is using SFRC-35 instead of plain concrete. The design capacity is calculated forehand according to BY-66.

5.4.4.1 Deflection of CRS+SFRC-35

Deflection at two critical points is elaborated in a graphical view to make it more understandable.

Slab-4 showed more resistance to deflection compared to CRS slab. Compare the following figure with Figure 80.

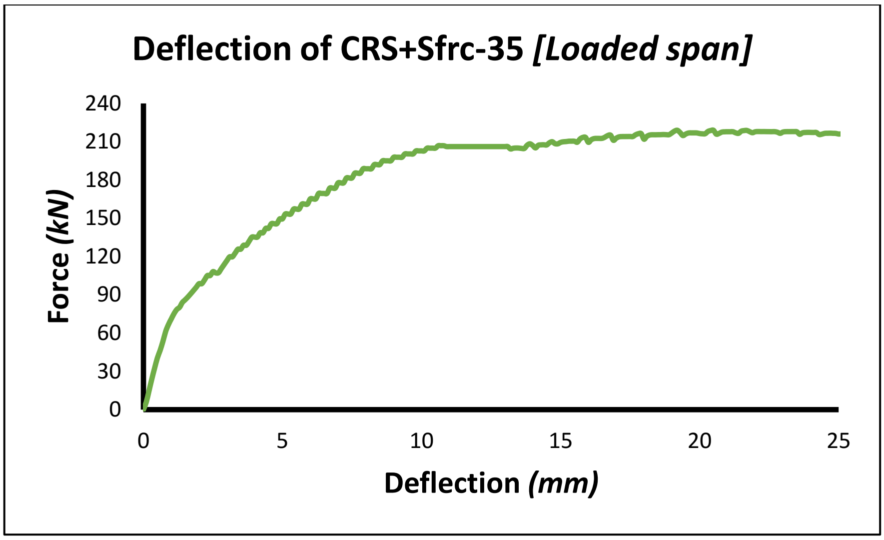

Figure 84: deflection of CRS+SFRC-35 [loaded span]

Same behavior is noted at centre support. Slab-4 was more resilient to deflection compared to CRS. Moreover, testing setup was unable to reach its failure point.

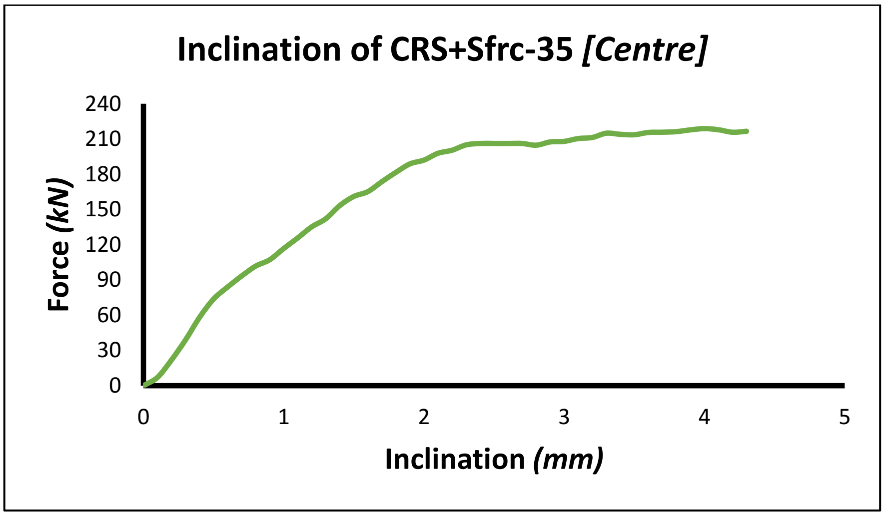

Figure 85: Inclination of CRS+SFRC-35 [Centre]

5.4.4.2 Deformation of CRS+SFRC-35

Deformation is discussed and taken as CMOD. Two cases are elaborated graphically at critical points.

Compared to CRS, cracks occurred at considerably higher loading. In this case, there were two entities which took the load after the loss of concrete´s own tensile strength.

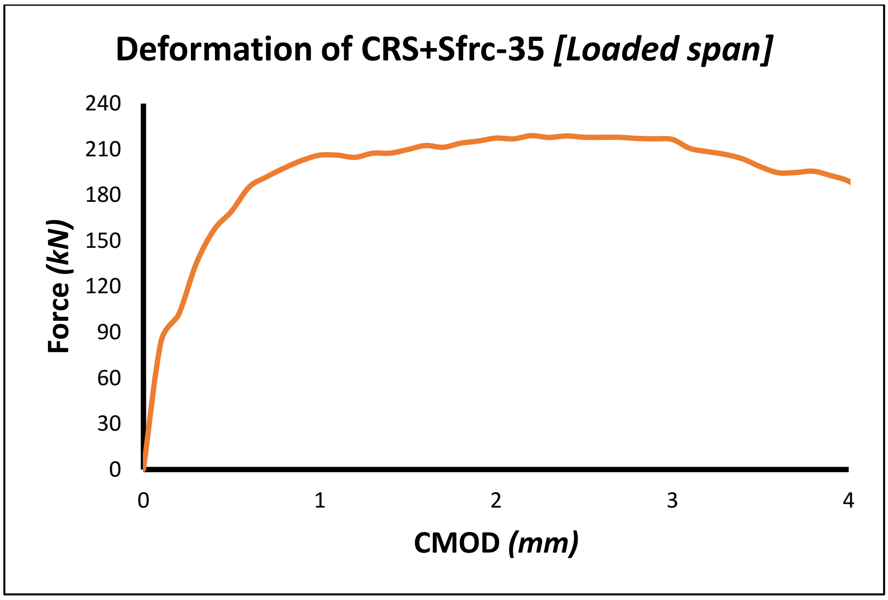

Figure 86: Deformation of CRS+SFRC-35 [Loaded span]

After the first minor crack, load is taken rebars and steel fibers. Main loading is retained by rebars while steel fibers are contributing towards reduced crack width. The sudden drop of load line in the following Figure 87 shows that some of the rebars have yielded and sheared off.

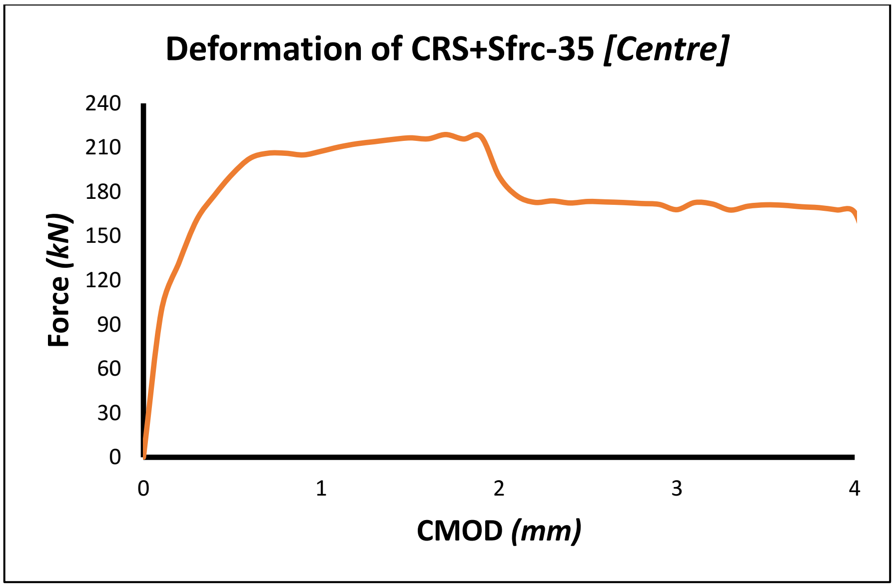

Figure 87: Deformation of CRS+SFRC-35 [Centre]

5.5 Comparison of slabs

An easy and effective way to study the behavioral changes with different dosages of steel fibers is to compare the slabs in the following manner.

1. Comparison of Slab-1 and Slab-2
2. Comparison of Slab-3 and Slab-4
3. Plotting all together

Above mentioned approach will help us study in detail any behavioral changes that are brought by increasing or inclusive steel fiber dosage.

5.5.1 Comparison of Slab-1 and Slab-2

Both of the stated slabs are pure steel fiber reinforced concrete slabs with no conventional reinforcement inside. Deflection and deformation comparisons are carried out to understand both the material reaction. The resistivity against deflection and deformation can also summarise the results whether steel fiber reinforced concrete is showing resistive nature or vice versa. Moreover, comparison will also clarify if additional steel fibers bring any additional resistances to load and improved strengths.

5.5.1.1 Deflection comparison of Slab-1 and Slab-2

Figure 88 elaborates the difference of resistance to deflection of two different steel fiber dosages. It can be seen that both slab specimen took the load equally with negligible difference but after the croos-section is cracked, reducing the effective depth of concrete slab, lesser steel fiber dosage results in significant strength drop while the higher steel fiber dosage is still capable of taking the load.

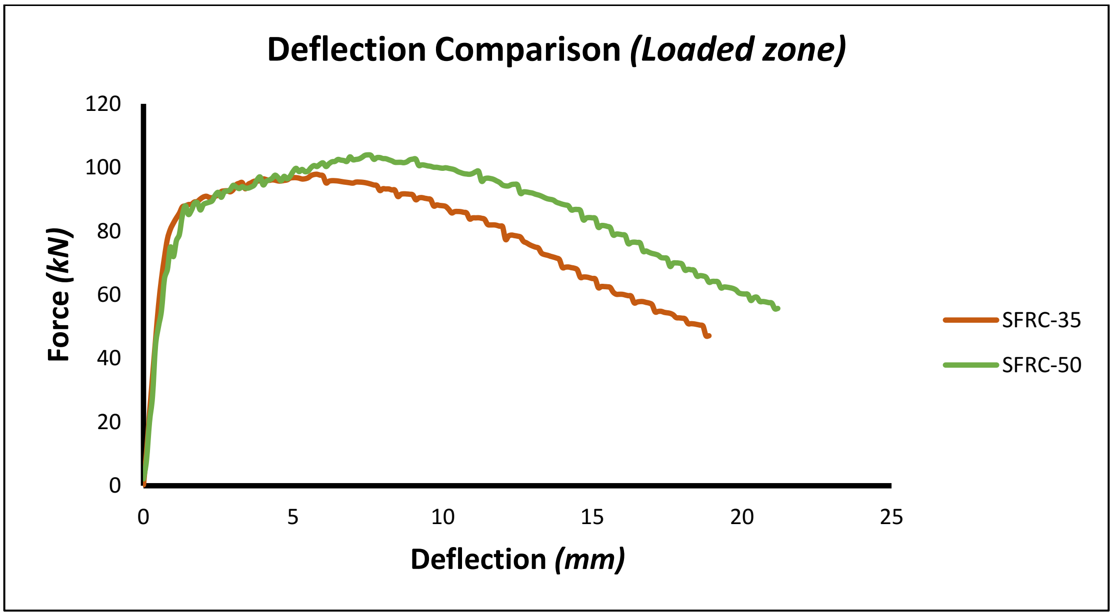

Figure 88: Deflection comparison of Slab-1 and Slab-2 [Loaded zone]

Centre support is critical in five-point testing setup and the crack/failure was supposed to occur at centre. Same behavior resulted at centre point too showing reduced strength of smaller steel fiber dosages while extra resistance to deflection was noted against higher steel fiber dosages.

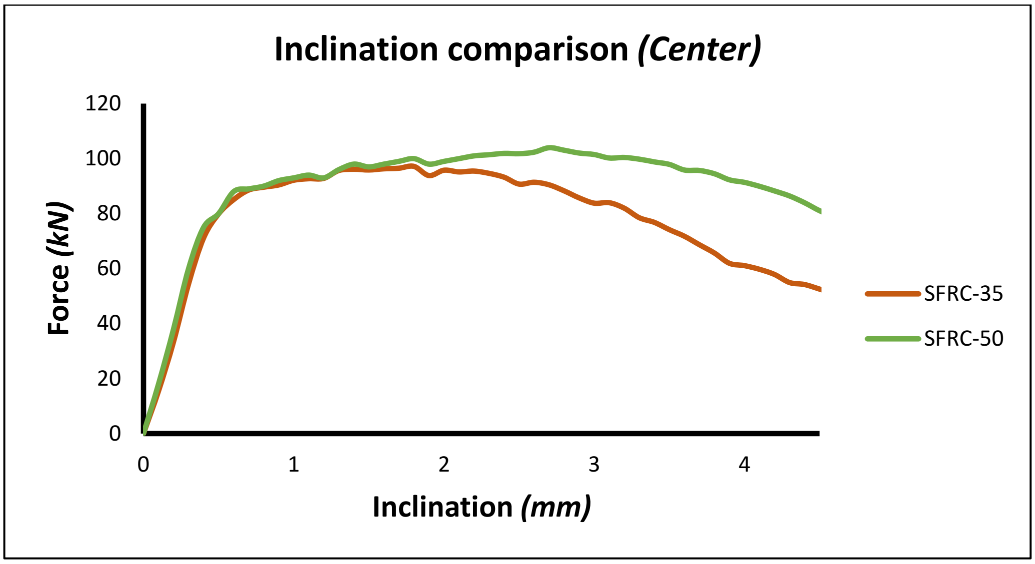

Figure 89: Inclination comparison of Slab-1 and Slab-2 [Centre]

Higher steel fiber dosage provided extra strength and resistance to deflection. Additionally, it also prolonged the load bearability. The response of a slab with higher steel fiber dosage is more stable and linear compared to a slab with less dense steel fiber dose.

5.5.1.2 Deformation comparison of Slab-1 and Slab-2

Deformation is taken as crack opening and extracted from strains. The results at two different points are compared i.e. loaded zone and centre point.

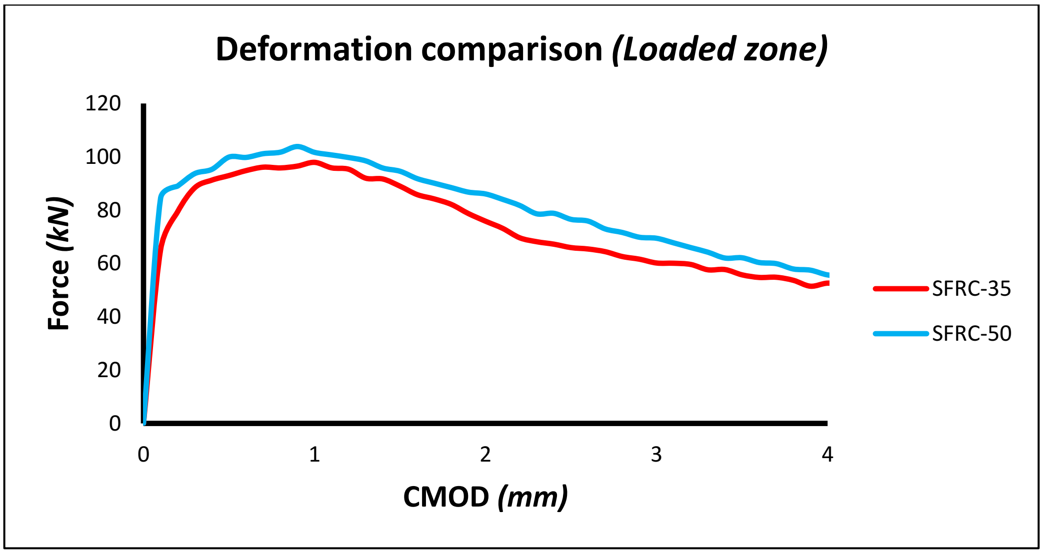

Figure 90: Deformation comparison of Slab-1 and Slab-2 [Loaded zone]

It is clear from Figure 90 that SFRC-50 slab showed more resistance to crack compared to SFRC-35 slab. This is due to the greater density of steel fibers present in the concrete matrix.

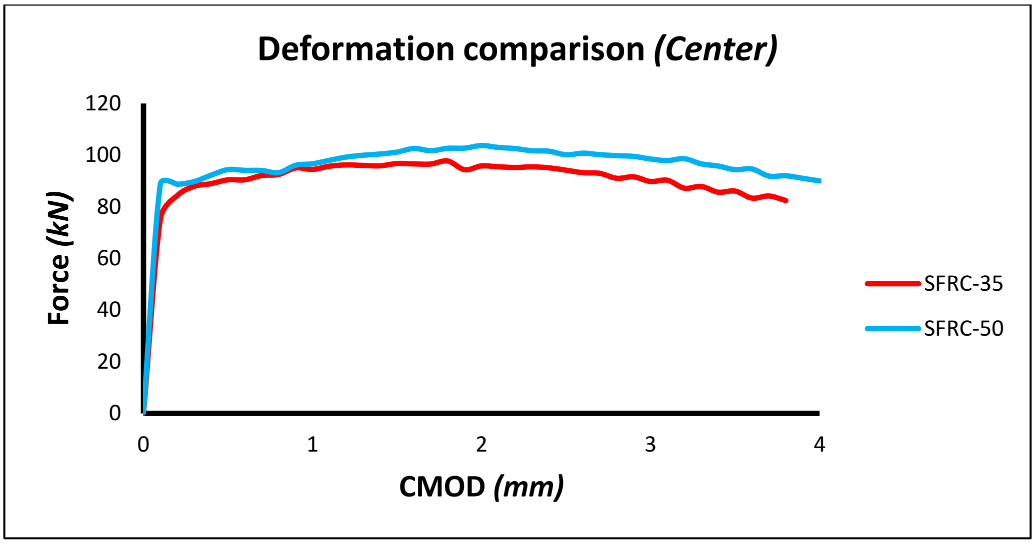

Figure 91: Deformation comparison of Slab-1 and Slab-2 [Centre]

Both above mentioned figures are showing results at two different locations yet portray the same behavior. It can be concluded from the results that greater the steel fiber dosage, greater is the resistance to crack appearance.

5.5.2 Comparison of Slab-3 and Slab-4

It is logical to compare above mentioned slabs because of the materialistic similarity. Slab-3 is casted out of plain concrete with conventional reinforcements while Slab-4 is casted replacing plain concerte by SFRC-35 and the conventional reinforcements remained unchanged.

5.5.2.1 Deflection comparison of Slab-3 and Slab-4

Concrete is a brittle material and deflection can result in sudden collapse. Ordinary rebars are usually induced to support deflection and increase the resistance to exposed load cases.

In the following passage, comparison of pure conventionally reinforced slab and steel fiber reinforced concrete with conventional reinforcement is elaborated. The resistance to deflection and any enhancement of strength can be clearly seen with the replacement of plain concrete with steel fibers.

Steel fiber dosage used in Slab-4 is 35kg/m^3. The moment capacity was calculated forehand and mentioned in Appendix-B.

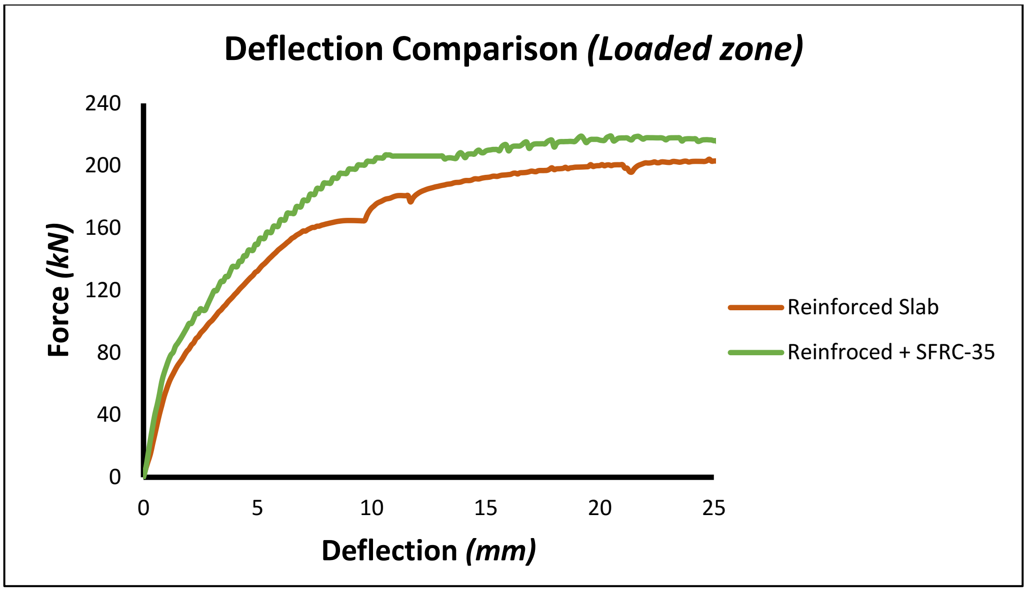

Figure 92: Deflection comparison of Slab-3 and Slab-4 [Loaded zone]

It is clear from the figure that the replacement of plain concrete with steel fiber reinforced concrete brings positive resistance against deflection.

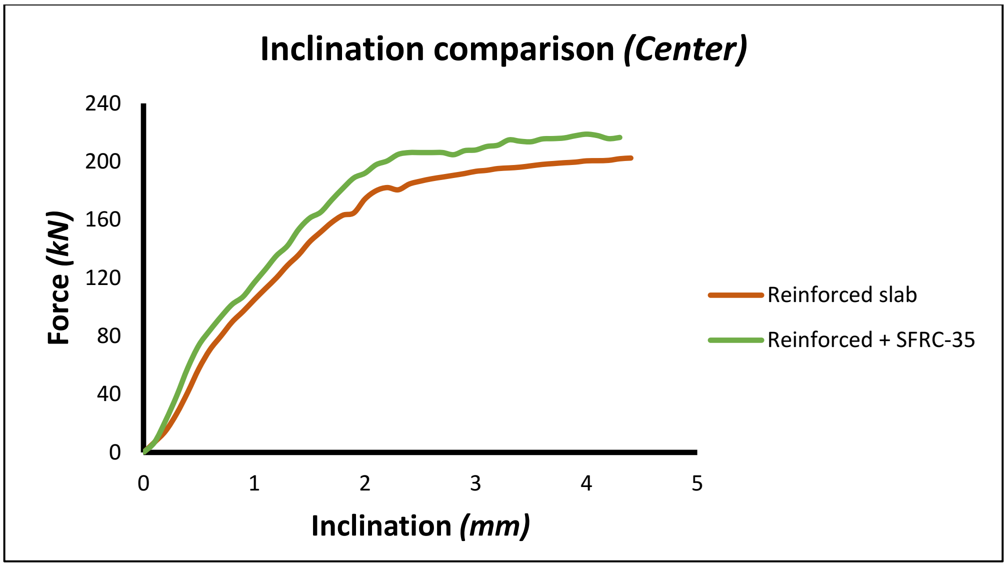

Figure 93: Inclination comparison of Slab-3 and Slab-4 [Centre]

Both graphs translate extra strengths with reduced deflection in case of Slab-4 which is a combination slab of steel fiber reinforced concrete with steel fiber dosage of 35kg/m^3 and conventional reinforcements. The peak loading is also altered and enhanced by the introduction of steel fibers compared to a slab with no steel fibers.

5.5.2.2 Deformation comparison of Slab-3 and Slab-4

Crack controlling is mandatory and have provisions in design guides. Deformations are taken in the sense of CMOD and are calculated out of strain values.

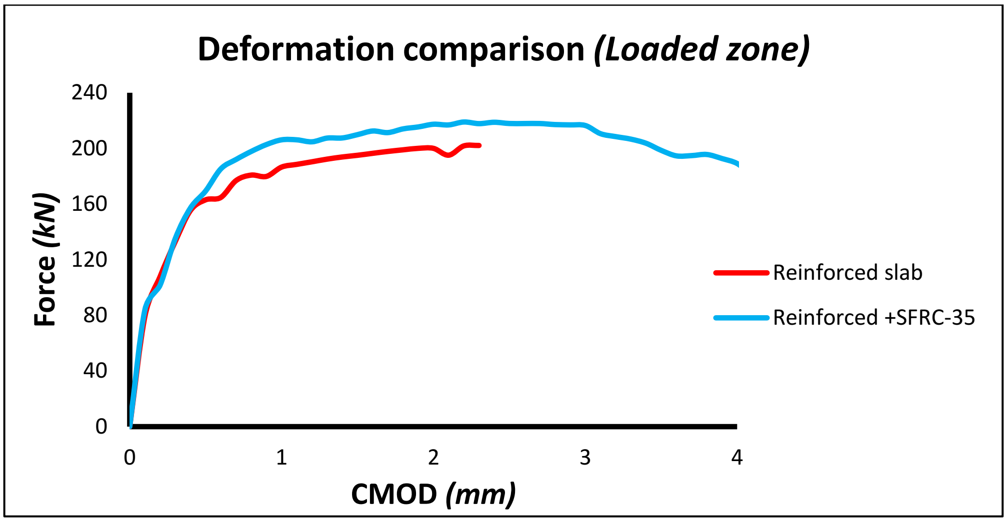

Figure 94: Deformation comparison of Slab-3 and Slab-4 [Loaded zone]

Steel fibers are genuinely considered as crack reducers or crack minimizers at particular load level. Crack reducing and load resistance, both, are enhanced by simply replacing plain concrete with steel fiber reinforced concrete.

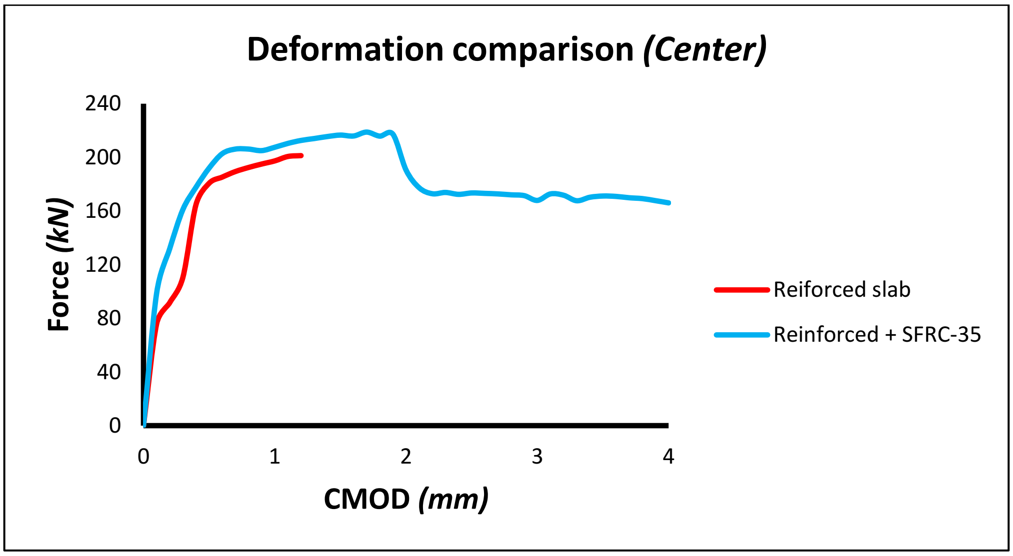

Figure 95: Deformation comparison of Slab-3 and Slab-4 [Centre]

Moreover, a concrete cross-section with only conventional reinforcement is still susceptible to brittle failure once all the steel bars yield and shear off. The same phenomenon can be seen in the above-mentioned figure. The sudden drop of load-line has resulted when some of rebars yielded and the load is transferred to the remaining bars instantaneously. Contrary, if there are conventional reinforcement and steel fibers both, the failure is not brittle after rebars yield because of the presence of steel fibers in the cross-section which will resist the load till whole of the cross-section cracks and the steel fibers are either sheared off or pulled out.

From the above mentioned figures, Figure 94 and Figure 95, it is clear that steel fibers work efficiently with conventional reinforcement. It improves crack resistance and load bearability. Furthermore, it also adds more reliability to structure by improving the ductility and load performance.

5.5.3 Comparison of all slabs

Earlier passages had elaborated the key comparisons, similarities and difference, in different slab specimen. This passage is dedicated to plot all the slab specimen for deflection and deformation all together.

5.5.3.1 Deflection graphs of all slab specimen

Following figures show deflection response of different slabs.

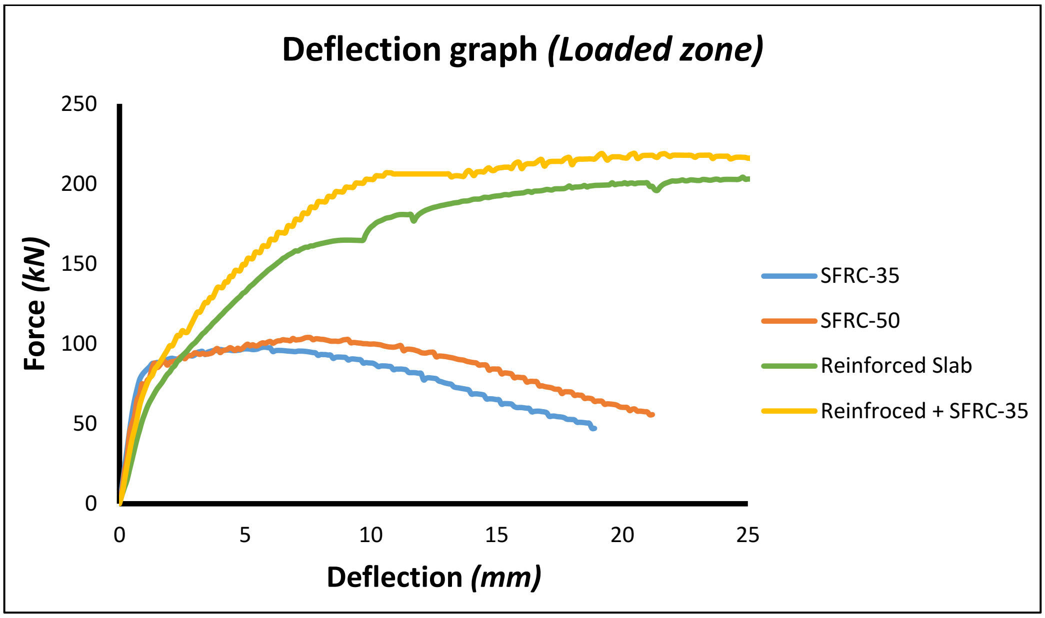

Figure 96: Deflection graph of all slab specimen [loaded zone]

Figure 96 combines all the plots mentioned and elaborated earlier under specific headings.

Moreover, it can be concluded from Figure 96 and Figure 97 that it is better to work with conventional reinforcement while using steel fiber reinforced concrete in case of major structural loads.

Form minor structural loads, especially a roof slab with no residential loads, steel fiber reinforced concrete slab can be an efficient and time saving solution.

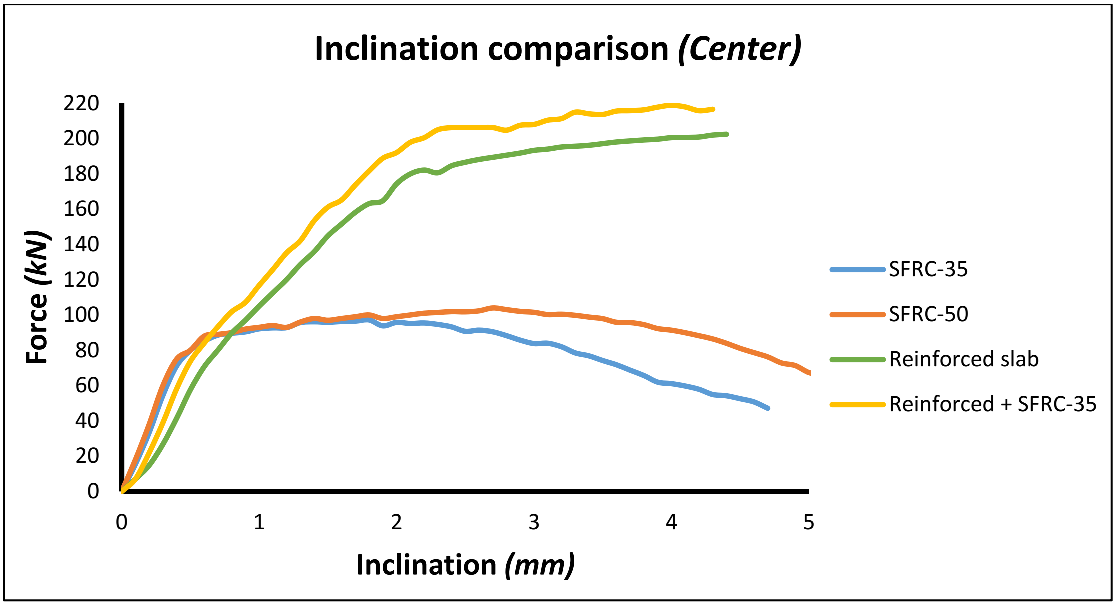

Figure 97: Inclination graph of all slab specimen [Centre]

Deflection check is a serviceability limit state issue and must be satisfied. The provisions are mentioned in Eurocodes for maximum and minimum deflection to satisfy a structure is sound and flexible. As it is clear from the Figure 96 and Figure 97 that steel fibers are actinig ductile but a sudden serious increase in load can result in disasterious situation. Furthermore, adding minimum conventional reinforcement is a good solution to address the problem.

5.5.3.2 Deformation graphs of all slab specimen

Deformations are referred as changed dimensions which can be concluded as cracks. Firstly, strain values were collected out of which crack widths are calculated.

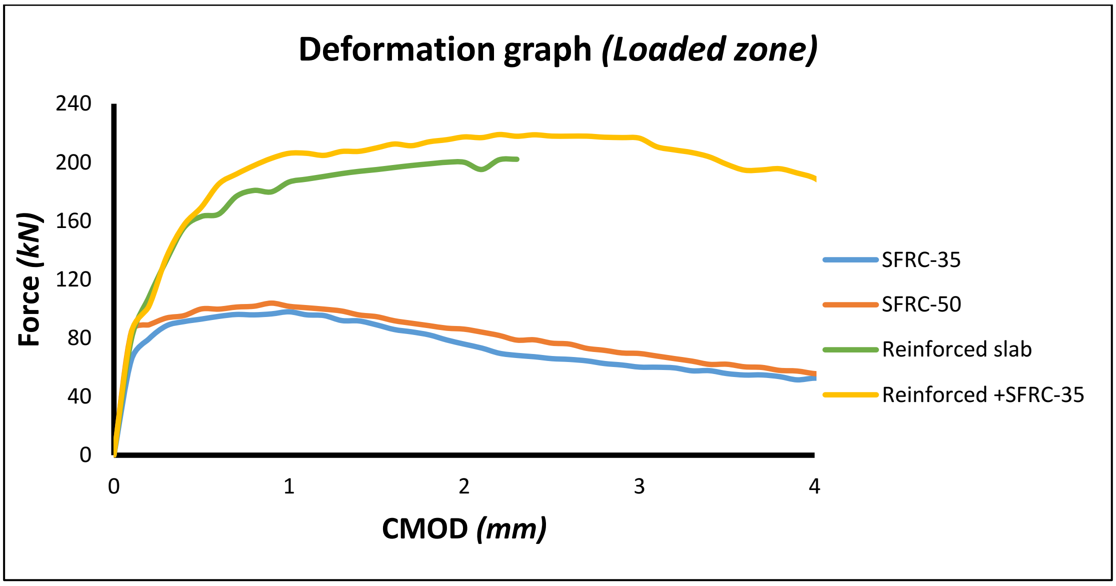

Figure 98: Deformation graph of all slab specimen [Loaded zone]

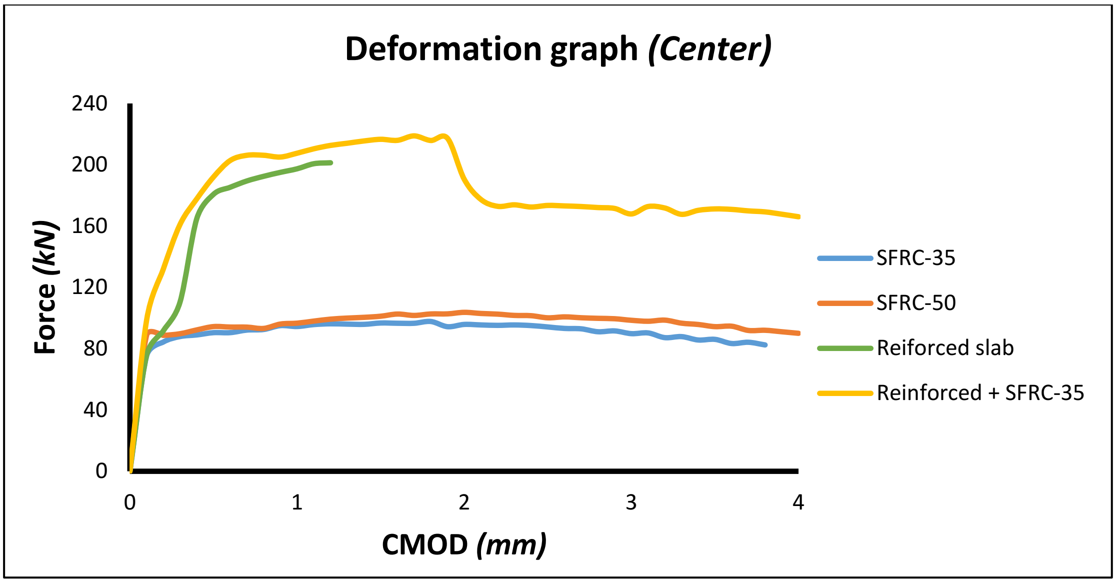

Figure 99: Deformation graph of all slab specimen [Centre]

Provisions are mentioned in Eurocodes for maximum and minimum crack widths. Mainly, 2,5mm crack width is considered maximum in case of using Eurocodes but it can vary in different national annexes.

Steel fibers are efficient in reducing crack widths and considerably adds to the strength of a structural member. Figure 98 and Figure 99 elaborates the effectiveness of steel fibers. Crack width are reduced or linearized while adding extra mechanical strengths.

From the above mentioned figure, it can be concluded that steel fibers are acting efficient and are ideal to control crack widths in a structure member.

5.6 Design and test strength comparison

The design moment capacities of slabs were calculated forehand according to the procedure provided in BY-66. Testing capacities were also extracted by simply neglecting every safety factor related to concrete, rebars and steel fibers.

Comparison of three slabs are provided as this thesis focuses on a material involving steel fibers. The comparison is provided between design moment capacity, moment capacity without safety factors, and moment capacity resulted from practical five-point bending slab test.

Design moment strength provides specific amount of safety factor against uneven and unexpected loadings. Eurocodes suggests to use safety values for specific material. Design strengths are mentioned in Figure 100.

Same design procedure was used to extract strength capacity without safety factors. All possible materialistic and loading safety factors were neglected and taken as a unit entity.

As mentioned before, the decided slab test setup is five-point bending test. It is selected so to keep the testing setup more adjacent to practical slab cases. A uniform line load was imposed and the capacities were noted down. Following figure shows the test resulted strength capacity.

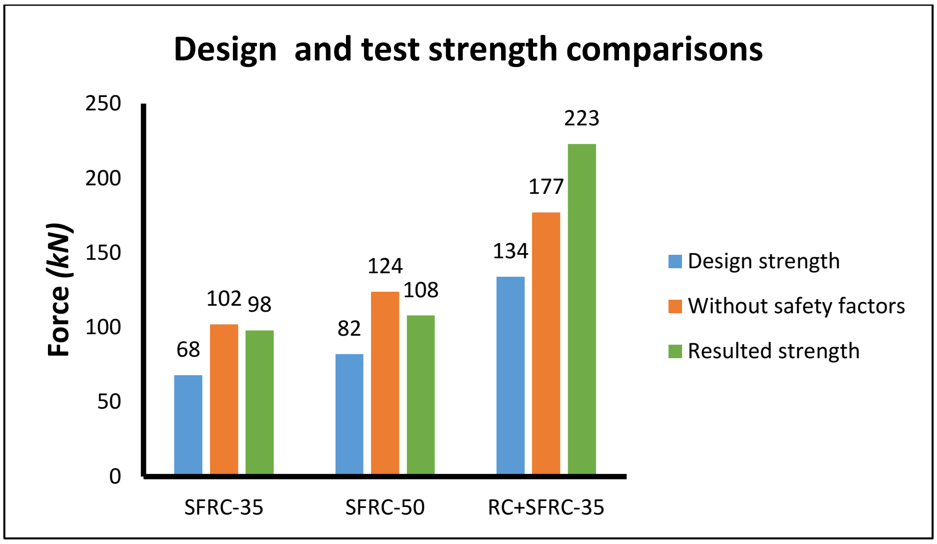

Figure 100: Design and test strength comparison

Following table shows the percentage of extra or deficiency of moment strengths of specific slab specimen.

Table 19: Comparison of moment capacities

Slab ID	Design force capacity	Force required without safety factors	Test resulted force capacity	Lag/Extra (- Lag) (+ Extra)			
				Design		Without safety factors	
	kN	*kN*	*kN*	*kN*	*%*	*kN*	*%*
SFRC-35	67	101	98	+31	+31	-3	-4
SFRC-50	81	122	108	+27	+25	-16	-13
RC+SFRC-35	134	177	223	+89	+40	+46	+21

5.7 Over-all Conclusion

For a material to be used for structural purposes, its failure approach must be taken into account. All the material and discussion provided above summarises that steel fiber reinforced concrete can be used for structural purposes. Its load retainability and crack reducing nature adds more to its load bearability.

Steel fiber reinforced concrete, all the dosages tested, showed strain hardening behavior comparatively to plain concrete with an efficient load bearing nature. Moreover, the failure mechanism was significantly linear and dropping with a lesser gradient rather sudden.

Previously, it was thought risky to use only steel fiber reinforced concrete without any conventional reinforcements. Two different slabs were tested with different steel fiber dosages which satisfied it design strength capacities. This is a proof for steel fiber reinforced concrete being able to be used for structural purposes individually and without conventional reinforcements as the results shows that it is satisfying the design capacities.

A combination slab is also tested including steel fibers and conventional reinforcement and signinficant reduction in cracking is noted against particular loading. Moreover, steel fibers also contributed in the enhancement of ultimate strength of slab specimen.

Besides adding flexural strengths, steel fibers also add to concrete´s compressive strengths and reduces crack formation significantly. Steel fibers resist formation of a major crack rather split it into multiple small cracks.

The results collected through experimentation shows that SFRC is fulfilling design criteria but lagging to satisfy test criteria. Such a deficit can be omitted through increasing safety factors related to design residual strengths. I recommend the following safety factors:

$$f_{ft.R.1} = 0.40 * f_{R.1}$$

$$f_{ft.R.3} = 0.30 * f_{R.3}$$

Using the above-mentioned safety factors can omit the deficit upto SFRC-50kg dosage. Denser dosages must be tested to insure the satisfaction of load capacity and safety factors must be altered, if required.

Test shows that SFRC, along conventional reinforcement, work efficient and optimum. Such a composite material is having sufficient safety strength to tackle accidental excessive loads. Moreover, conventional reinforcement can absorb energy while steel fibers reduce the cracks. I would recommend to use SFRC in combination with conventional reinforcements.

Contrary, slab specimen satisfied design strengths so they must be considered safe enough to be used. If the recommended safety factors related to design residual strengths are used in the design procedure, the design will be much safer. We can replace conventional reinforcements too, bu thicker slabs must be casted for such purpose and thicker slab is resulting in excessive dead load.

5.8 Future recommendations

Steel fiber reinforced concrete is still an emerging field with a lot of ongoing research. The research project discussed in the above whole document share a minor portion and there is a lot more which steel fibers can add to concrete industry.

Following are some of the future recommendations.

- Multiple slabs of a particular steel fiber dosage must be tested to get a better conclusion.
- Heavy dosages (>50 kg/m^3) should be introduced.
- At least six beam/slab specimen for each steel fiber dose.
- Efforts must be put to totally replace conventional reinforcement. Although it is still tough in major load scenarios but it can be done for minor load cases.
- Efforts must be put to reduce the use of conventional reinforcement by adding steel fibers. The procedure is provided in BY-66 which will be helpful while calculating design capacities with respect to residual flexural tensile strength of a particular steel fiber dosage and cross-sectional area of conventional reinforcement. Practical test will testify whether the designed entity satisfies the capacity or not.
- Efforts must be put to totally replace shear reinforcements or minimum conventional reinforcements. It can be done easily but tests are required to see if there are any anomalies.
- Workability of concrete plays an important role in its practicality. This thesis targeted S-3 slump class (100-150mm) and used super plasticisers to achieve required slump values. I recommend to use atleast S-4 slump class. Firstly, it will promote the homogeneity of steel fibers which is of utmost importance and secondly it will reduce casting efforts.
- Strain gauges, 150mm wide strain gauges are used in this thesis, used for future tests must have minimum width of 200mm especially in a case where there in conventional reinforcements involved. If not, 150mm wide strain guage is enough to trap expected crack and provide accurate values.
- In case of conventional reinforcement, if testing setup is deflection controlled, minimum loading rate should be kept 0.8mm/min. this helps in reduced testing time. Furthermore, insure that each loading jack has 500kN capacity.

APPLICATION SUGGESTIONS:

1. Pure SFRC:
    a. Small scale residential roofs (light roofs).
    b. Pile slabs or any slab with area support is good to be made up of SFR.
    c. Beams and columns. Beams must not be critical as there is still a lot of design research required to optimize and find a precise SFRC design approach.
    d. Grad-slabs or floors.
    e. Pavements.
    f. Roadside barriers either small scale or large.
    g. Concrete lining due to its durability and impermeability.
2. SFRC + Conventional Reinforcements:
    a. Major scale roofs.
    b. Major scale slabs i.e. residential, nuclear, commercial etc.
    c. Approaching deck of a bridge or pier slab in the foundation.
    d. Pile cover or pile slabs.
    e. Grad-slabs.
    f. Rigid structural joints.

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APPENDIX A:

RESIDUAL FLEXURAL TENSILE STRENGTH ACCORDING TO BY-66.

Following is the procedure of getting flexural tensile strength of Steel fiber reinforced concrete.

Crack Mouth Opening Displacement:

$$CMOD_{0.5} := 0.5mm$$

$$CMOD_{2.5} := 2.5mm$$

1. **SFRC-B-35**

Table 20: SFRC-B-35 specimens and forces at CMODs

	BEAM ID	Length	Width	Height	Forces at CMODs	
		l	b	h	$F_{0,5}$	$F_{2,5}$
		mm	*mm*	*mm*	*kN*	*kN*
SFRC-B-35	1	500	150	149	20,2	22,1
	2	500	149	149	17,7	14,8
	3	500	149	150	16,2	15,0
	4	500	149	150	15,0	16,8
	5	500	149,5	150	20,6	17,4
	6	500	149,5	150	18,4	17,1
Mean Strengths		$f_{R.1}$			4,0 N/mm²	
		$f_{R.3}$			3,9 N/mm²	
Characteristic Design Strengths		$f_{ft.R.1}$			1,8 N/mm²	
		$f_{ft.R.3}$			1,5 N/mm²	

Finding design values against the above mentioned Table 18.

i. SFRC-B-35-1

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 4.549 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 4.977 \cdot \frac{N}{mm^2}$$

ii. SFRC-B-35-2

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 4.013 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 3.356 \cdot \frac{N}{mm^2}$$

iii. SFRC-B-35-3

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 3.579 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 3.356 \cdot \frac{N}{mm^2}$$

iv. SFRC-B-35-4

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 3.356 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 3.758 \cdot \frac{N}{mm^2}$$

v. SFRC-B-35-5

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 4.593 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 3.88 \cdot \frac{N}{mm^2}$$

vi. SFRC-B-35-6

Residual tensile strengths;

$$f_{R.1} := \frac{3 \cdot F_{0.5} \cdot l}{2 \cdot b \cdot h^2} = 4.103 \cdot \frac{N}{mm^2}$$

$$f_{R.3} := \frac{3 \cdot F_{2.5} \cdot l}{2 \cdot b \cdot h^2} = 3.813 \cdot \frac{N}{mm^2}$$

The mean residual strengths, mentioned below, are used for design purposes.

$f_{R.1}$ = 4.0 N/mm^2

$f_{R.3}$ = 3.9 N/mm^2

Characterisitc residual tensile strengths;

$f_{ft.R.1}$ = 0.45 * $f_{R.1}$ = 1.8 N/mm^2

$f_{ft.R.3}$ = 0.37 * $f_{R.3}$ = 1.5 N/mm^2

The above stated procedure is adopted to find residual flexure tensile strength of the rest of steel fiber dosages. Following tables show the resulted values only.

2. SFRC-B-50

Table 21: SFRC-B-50 specimens and forces at CMODs

BEAM ID		Length	Width	Height	Forces at CMODs	
		l	**b**	**h**	**$F_{0,5}$**	**$F_{2,5}$**
		mm	*mm*	*mm*	*kN*	*kN*
SFRC-B-50	1	500	150	150	20,0	21,2
	2	500	150	150	22,4	24,7
	3	500	150	150	21,6	21,2
	4	500	150	150	21,6	19,8
	5	500	149	150	19,2	19,7
	6	500	150	150	23,6	22,1

Mean Stengths	$f_{R.1}$	4,8 N/mm^2
	$f_{R.3}$	4,8 N/mm^2
Characteristic Design Strengths	$f_{ft.R.1}$	2,1 N/mm^2
	$f_{ft.R.3}$	1,8 N/mm^2

3. SFRC-B-75

Table 22: SFRC-B-75 specimens and forces at CMODs

	BEAM ID	Length	Width	Height	Forces at CMODs	
		l	b	h	$F_{0,5}$	$F_{2,5}$
		mm	*mm*	*mm*	*kN*	*kN*
SFRC-B-75	1	500	150	150	27,2	25,5
	2	500	150	150	26,1	25,6
	3	500	150	150	23,2	21,6
	4	500	150	150	23,0	22,2
	5	500	150	150	30,6	27,1
	6	500	150	150	27,3	21,75

Mean Strengths	$f_{R.1}$	5,8 N/mm^2
	$f_{R.3}$	5,3 N/mm^2
Characteristic Design Strengths	$f_{ft.R.1}$	2,6 N/mm^2
	$f_{ft.R.3}$	2,0 N/mm^2

4. SFRC-B-100

Table 23: SFRC-B-100 specimens and forces at CMODs

BEAM ID		Length	Width	Height	Forces at CMODs	
		l	b	h	$F_{0,5}$	$F_{2,5}$
		mm	*mm*	*mm*	*kN*	*kN*
SFRC-B-100	1	500	150	150	27,2	25,5
	2	500	150	150	26,1	24,7
	3	500	150	150	23,2	21,6
	4	500	150	150	23,0	22,2
	5	500	150	150	30,6	27,1
	6	500	150	150	27,3	21,75
Mean Strengths		$f_{R.1}$			7,1 N/mm²	
		$f_{R.3}$			7,1 N/mm²	
Characteristic Design Strengths		$f_{ft.R.1}$			3,2 N/mm²	
		$f_{ft.R.3}$			2,6 N/mm²	

Following is a summarized table stating residual flexural tensile strengths of all steel fiber dosages.

Table 24: Residual flexural tensile strengths of all steel fiber dosages

Description	$f_{R.1}$	$f_{R.3}$
SFRC-35	4.0	3.9
SFRC-50	4.8	4.8
SFRC-75	5.8	5.3
SFRC-100	7.1	7.1

APPENDIX B:

SLAB DESIGN PROCEDURE ACCORDING TO BY-66.

Following is the procedure of designing SFRC slab in accordance to BY-66.

1. ***Without conventional Reinforcements:***

Steel fiber Hendix Prime XP 75/62:

Dosage: SFRC-35 kg/m³

a. **Slab Dimensions:**

Slab depth $h := 220mm$

Width of slab $b := 1200mm$

b. **Concrete Properties:**

Density of concrete $\rho_c := 25\frac{kN}{m^3}$

Concrete cover $c_{nom} := 25mm$

Factor $\gamma_c := 1.5$

Long-term coefficient $\alpha_{cc} := 0.85$

$\alpha_{ct} := 1.0$

Characteristic Strength $f_{ck} := 45MPa$

Design Strength $f_{cd} := \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} = 25.5 \cdot MPa$

Average strength $f_{cm} := f_{ck} + 8MPa = 53 \cdot MPa$

Characteristic Tensile strength $f_{ctm} := 0.3 \cdot \left(\frac{f_{ck}}{MPa}\right)^{\frac{2}{3}} \cdot MPa = 3.795 \cdot MPa$

$f_{ctk0.05} := 0.7 \cdot f_{ctm} = 2.657 \cdot MPa$

Design Tensile Strength $f_{ctd} := \alpha_{ct} \cdot \frac{f_{ctk0.05}}{\gamma_c} = 1.771 \cdot MPa$

Modulus of Elasticity $E_{cm} := 22 \cdot \left(\frac{f_{cm}}{10MPa}\right)^{0.3} \cdot GPa = 36.283 \cdot GPa$

c. Steel Fiber Properties:

Density $\rho_f := 7850 \frac{kg}{m^3}$

Factors $\gamma_f := 1.5$ $\gamma_{f.SLS} := 1.0$

Residual Tensile Strengths

Class-R1 $f_{R1} := 4.0MPa$

Class-R3 $f_{R3} := 3.9MPa$

Characteristic Tensile Strengths

Class-R1 $f_{ft.R1} := 0.45 \cdot f_{R1} = 1.8 \cdot MPa$

Class-R3 $f_{ft.R3} := 0.37 \cdot f_{R3} = 1.443 \cdot MPa$

d. Design Tensile Strengths:

Ultimate Limit State:

Orientation Factor $\eta_f := 1.0$

Structural Factor $\eta_{det} := 2$

Class-R1 $f_{ftd.R1} := \eta_f \cdot \eta_{det} \cdot \frac{f_{ft.R1}}{\gamma_f} = 2.4 \cdot MPa$

Class-R3 $f_{ftd.R3} := \eta_f \cdot \eta_{det} \cdot \frac{f_{ft.R3}}{\gamma_f} = 1.924 \cdot MPa$

Serviceability Limit State:

Class-R1 $f_{ftd.R1.SLS} := \eta_f \cdot \frac{f_{ft.R1}}{\gamma_{f.SLS}} = 1.8 \cdot MPa$

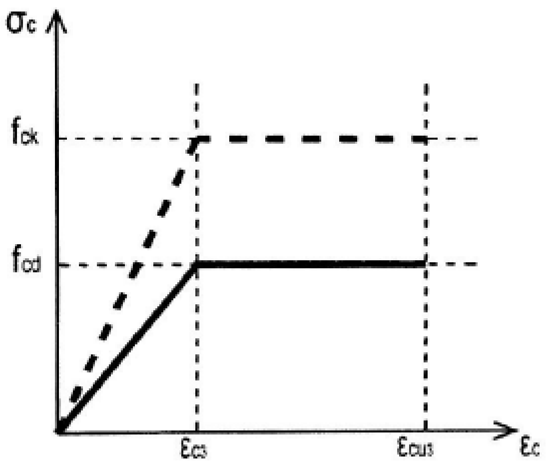
Ductility check:

$$C_1 := 100 \cdot \frac{f_{R1}}{f_{ctk0.05}} = 150.556$$

$$C_3 := 100 \cdot \frac{f_{R3}}{f_{R1}} = 97.5$$

$$Check_{C1} := \begin{cases} \text{"Ok"} & \text{if } C_1 \geq 75 \\ \text{"Not Ok"} & \text{otherwise} \end{cases} = \text{"Ok"}$$

$$Check_{C3} := \begin{cases} \text{"Ok"} & \text{if } C_3 \geq 65 \\ \text{"Not Ok"} & \text{otherwise} \end{cases} = \text{"Ok"}$$



Fiber Ultimate pull-strength $\sigma_f := f_{ftd.R3} = 1.924 \cdot MPa$

Tensile strain $\varepsilon_{ct} := \frac{f_{ctd}}{E_{cm}} = 4.882 \times 10^{-3} \cdot \%$

Specimen Depth $l_{cs} := h = 220 \cdot mm$

Crack Width $w := 2.5mm$

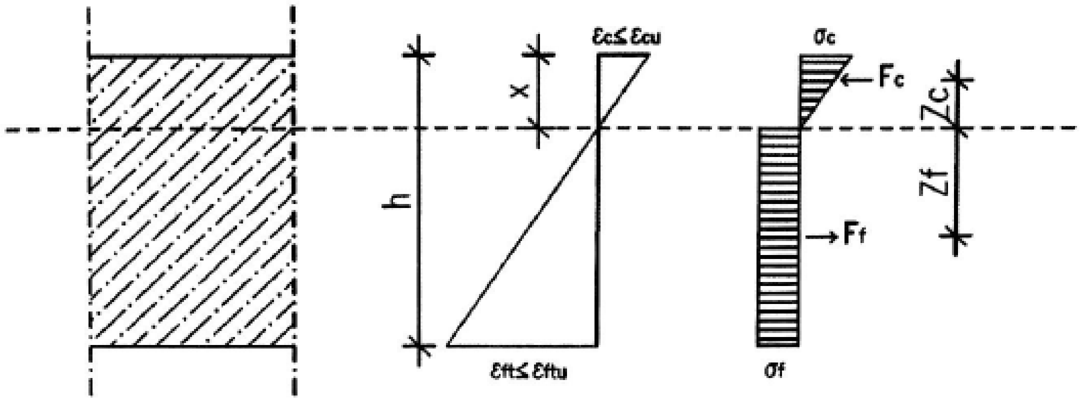
Ultimate fiber strain $\varepsilon_{ftu} := \varepsilon_{ct} + \frac{w}{l_{cs}} = 1.141 \cdot \%$

Compression strain $\varepsilon_c := \frac{\varepsilon_{ftu} \cdot x}{h - x}$

$\varepsilon_{c3} := 0.175\%$

Compression Stress $\sigma_c := f_{cd} \cdot \frac{\varepsilon_c}{\varepsilon_{c3}}$

As we know, $F_c := F_f + F_{st}$



$$f_{cd}\cdot\frac{\frac{\varepsilon_{ftu}\cdot x}{h-x}}{\varepsilon_{c3}}\cdot b\cdot\frac{x}{2} = \sigma_f\cdot b\cdot(h-x) + A_s\cdot f_{yd}$$

$$x_1 := -\frac{-2\cdot h\cdot\sigma_f\cdot\varepsilon_{c3} - \sqrt{2}\cdot h\cdot\sqrt{f_{cd}\cdot\sigma_f\cdot\varepsilon_{c3}\cdot\varepsilon_{ftu}}}{f_{cd}\cdot\varepsilon_{ftu} - 2\cdot\sigma_f\cdot\varepsilon_{c3}} = 39.47\cdot mm$$

$$x_2 := \frac{\sqrt{2}\cdot h\cdot\sqrt{f_{cd}\cdot\sigma_f\cdot\varepsilon_{c3}\cdot\varepsilon_{ftu}} - 2\cdot h\cdot\sigma_f\cdot\varepsilon_{c3}}{f_{cd}\cdot\varepsilon_{ftu} - 2\cdot\sigma_f\cdot\varepsilon_{c3}} = 29.047\cdot mm$$

$$x := \min(x_1, x_2) = 29.047\cdot mm$$

$$x = 29.047\cdot mm$$

$$\varepsilon_c := \frac{\varepsilon_{ftu}\cdot x}{h-x} = 0.174\cdot\%$$

$$\sigma_c := f_{cd}\cdot\frac{\varepsilon_c}{\varepsilon_{c3}} = 25.296\cdot MPa$$

Compression Forces

$$F_c := f_{cd}\cdot\frac{\frac{\varepsilon_{ftu}\cdot x}{h-x}}{\varepsilon_{c3}}\cdot b\cdot\frac{x}{2} = 440.872\cdot kN$$

Fiber Tension Forces

$$F_f := \sigma_f\cdot b\cdot(h-x) = 440.872\cdot kN$$

e. **Moment Capacity:**

$$M_{Rd} := F_c\cdot\frac{2}{3}\cdot x + F_f\cdot\frac{h-x}{2} = 50.63\cdot kN\cdot m$$

Steel fiber Hendix Prime XP 75/62:

Dosage: 50 kg/m³

a. Slab Dimensions:

Slab depth $h := 220mm$

Width of slab $b := 1200mm$

b. Concrete Properties:

Density of concrete $\rho_c := 25\frac{kN}{m^3}$

Concrete cover $c_{nom} := 25mm$

Factor $\gamma_c := 1.5$

Long-term coefficient $\alpha_{cc} := 0.85$

$\alpha_{ct} := 1.0$

Characteristic Strength $f_{ck} := 45MPa$

Design Strength $f_{cd} := \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} = 25.5 \cdot MPa$

Average strength $f_{cm} := f_{ck} + 8MPa = 53 \cdot MPa$

Characteristic Tensile strength $f_{ctm} := 0.3 \cdot \left(\frac{f_{ck}}{MPa}\right)^{\frac{2}{3}} \cdot MPa = 3.795 \cdot MPa$

$f_{ctk0.05} := 0.7 \cdot f_{ctm} = 2.657 \cdot MPa$

Design Tensile Strength $f_{ctd} := \alpha_{ct} \cdot \frac{f_{ctk0.05}}{\gamma_c} = 1.771 \cdot MPa$

Modulus of Elasticity $E_{cm} := 22 \cdot \left(\frac{f_{cm}}{10MPa}\right)^{0.3} \cdot GPa = 36.283 \cdot GPa$

c. Steel Fiber Properties:

Density $\rho_f := 7850\frac{kg}{m^3}$

Factors $\gamma_f := 1.5$ $\gamma_{f.SLS} := 1.0$

Residual Tensile Strengths

Class-R1 $f_{R1} := 4.8MPa$

Class-R3 $f_{R3} := 4.8MPa$

Characteristic Tensile Strengths

Class-R1 $f_{ft.R1} := 0.45 \cdot f_{R1} = 2.16 \cdot MPa$

Class-R3 $f_{ft.R3} := 0.37 \cdot f_{R3} = 1.776 \cdot MPa$

d. Design Tensile Strengths:

Ultimate Limit State:

Orientation Factor $\eta_f := 1.0$

Structural Factor $\eta_{det} := 2$

Class-R1 $f_{ftd.R1} := \eta_f \cdot \eta_{det} \cdot \dfrac{f_{ft.R1}}{\gamma_f} = 2.88 \cdot MPa$

Class-R3 $f_{ftd.R3} := \eta_f \cdot \eta_{det} \cdot \dfrac{f_{ft.R3}}{\gamma_f} = 2.368 \cdot MPa$

Serviceability Limit State:

Class-R1 $f_{ftd.R1.SLS} := \eta_f \cdot \dfrac{f_{ft.R1}}{\gamma_{f.SLS}} = 2.16 \cdot MPa$

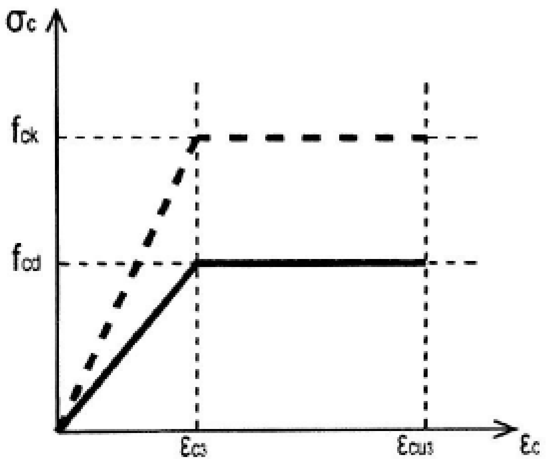
Ductility check:

$$C_1 := 100 \cdot \frac{f_{R1}}{f_{ctk0.05}} = 180.668$$

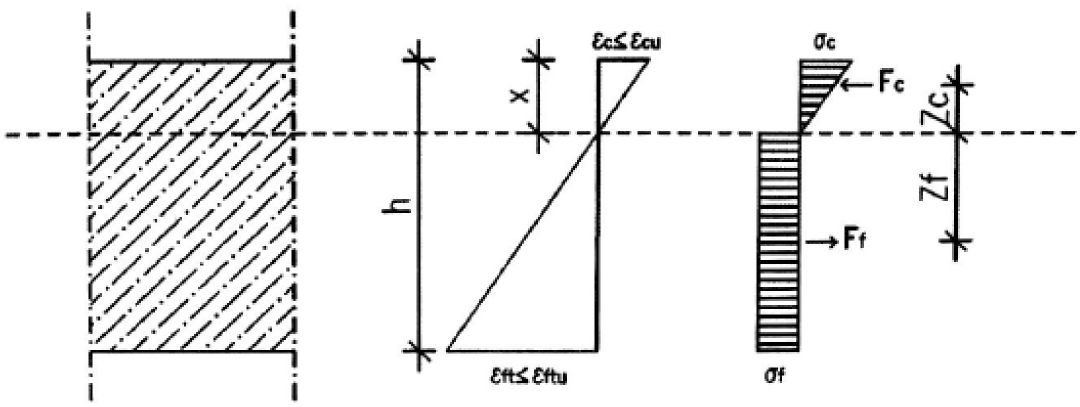
$$C_3 := 100 \cdot \frac{f_{R3}}{f_{R1}} = 100$$

$$Check_{C1} := \begin{cases} \text{"Ok"} & \text{if } C_1 \geq 75 \\ \text{"Not Ok"} & \text{otherwise} \end{cases} = \text{"Ok"}$$

$$Check_{C3} := \begin{cases} \text{"Ok"} & \text{if } C_3 \geq 65 \\ \text{"Not Ok"} & \text{otherwise} \end{cases} = \text{"Ok"}$$



Fiber Ultimate pull-strength	$\sigma_f := f_{ftd.R3} = 2.368 \cdot MPa$
Tensile strain	$\varepsilon_{ct} := \frac{f_{ctd}}{E_{cm}} = 4.882 \times 10^{-3} \cdot \%$
Specimen Depth	$l_{cs} := h = 220 \cdot mm$
Crack Width	$w := 2.5mm$
Ultimate fiber strain	$\varepsilon_{ftu} := \varepsilon_{ct} + \frac{w}{l_{cs}} = 1.141 \cdot \%$
Compression strain	$\varepsilon_c := \frac{\varepsilon_{ftu} \cdot x}{h - x}$
	$\varepsilon_{c3} := 0.175\%$
Compression Stress	$\sigma_c := f_{cd} \cdot \frac{\varepsilon_c}{\varepsilon_{c3}}$
As we know,	$F_c := F_f + F_{st}$



$$f_{cd}\cdot\frac{\frac{\varepsilon_{ftu}\cdot x}{h-x}}{\varepsilon_{c3}}\cdot b\cdot\frac{x}{2} = \sigma_f\cdot b\cdot(h-x) + A_s\cdot f_{yd}$$

$$x_1 := -\frac{-2\cdot h\cdot\sigma_f\cdot\varepsilon_{c3} - \sqrt{2}\cdot h\cdot\sqrt{f_{cd}\cdot\sigma_f\cdot\varepsilon_{c3}\cdot\varepsilon_{ftu}}}{f_{cd}\cdot\varepsilon_{ftu} - 2\cdot\sigma_f\cdot\varepsilon_{c3}} = 44.664\cdot mm$$

$$x_2 := \frac{\sqrt{2}\cdot h\cdot\sqrt{f_{cd}\cdot\sigma_f\cdot\varepsilon_{c3}\cdot\varepsilon_{ftu}} - 2\cdot h\cdot\sigma_f\cdot\varepsilon_{c3}}{f_{cd}\cdot\varepsilon_{ftu} - 2\cdot\sigma_f\cdot\varepsilon_{c3}} = 31.766\cdot mm$$

$$x := \min(x_1, x_2) = 31.766\cdot mm$$

$$x = 31.766\cdot mm$$

$$\varepsilon_c := \frac{\varepsilon_{ftu}\cdot x}{h-x} = 0.193\cdot\%$$

$$\sigma_c := f_{cd}\cdot\frac{\varepsilon_c}{\varepsilon_{c3}} = 28.064\cdot MPa$$

Compression Forces

$$F_c := f_{cd}\cdot\frac{\frac{\varepsilon_{ftu}\cdot x}{h-x}}{\varepsilon_{c3}}\cdot b\cdot\frac{x}{2} = 534.886\cdot kN$$

Fiber Tension Forces

$$F_f := \sigma_f\cdot b\cdot(h-x) = 534.886\cdot kN$$

e. Moment Capacity:

$$M_{Rd} := F_c\cdot\frac{2}{3}\cdot x + F_f\cdot\frac{h-x}{2} = 61.669\cdot kN\cdot m$$

----

2. With conventional Reinforcements:

Steel fiber Hendix Prime XP 75/62:

Dosage: 35 kg/m³

a. Slab Dimensions:

Slab depth $h := 200mm$

Width of slab $b := 1200mm$

b. Concrete Properties:

Density of concrete $\rho_c := 25\frac{kN}{m^3}$

Concrete cover $c_{nom} := 25mm$

Factor $\gamma_c := 1.5$

Long-term coefficient $\alpha_{cc} := 0.85$

$\alpha_{ct} := 1.0$

Characteristic Strength $f_{ck} := 45MPa$

Design Strength $f_{cd} := \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} = 25.5 \cdot MPa$

Average strength $f_{cm} := f_{ck} + 8MPa = 53 \cdot MPa$

Characteristic Tensile strength $f_{ctm} := 0.3 \cdot \left(\frac{f_{ck}}{MPa}\right)^{\frac{2}{3}} \cdot MPa = 3.795 \cdot MPa$

$f_{ctk0.05} := 0.7 \cdot f_{ctm} = 2.657 \cdot MPa$

Design Tensile Strength $f_{ctd} := \alpha_{ct} \cdot \frac{f_{ctk0.05}}{\gamma_c} = 1.771 \cdot MPa$

Modulus of Elasticity $E_{cm} := 22 \cdot \left(\frac{f_{cm}}{10MPa}\right)^{0.3} \cdot GPa = 36.283 \cdot GPa$

c. Conventional reinforcement properties:

Characteristic yielding strength $f_{yk} := 500MPa$

Safety factor $\gamma_s := 1.15$

Design yielding strength $f_{yd} := \frac{f_{yk}}{\gamma_s} = 434.783 \cdot MPa$

Modulus of Elasticity $E_s := 200GPa$

Dia of bar used $\phi_b := 8mm$

Area of reinforcement $A_s := 854mm^2$

Effective depth $d := h - c_{nom} - \frac{\phi_b}{2} = 171 \cdot mm$

Effective compression depth

$$\lambda := \begin{vmatrix} 0.8 \text{ if } f_{ck} \le 50MPa \\ \left[0.8 - \left(\frac{f_{ck}}{MPa} - 50\right) \cdot \frac{1}{400}\right] \text{ if } 50MPa < f_{ck} < 90MPa \end{vmatrix} = 0.8$$

Adjusting effective strength

$$\eta := \begin{vmatrix} 1.0 \text{ if } f_{ck} \le 50MPa \\ \left[1.0 - \left(\frac{f_{ck}}{MPa} - 50\right) \cdot \frac{1}{200}\right] \text{ if } 50MPa < f_{ck} < 90MPa \end{vmatrix} = 1$$

d. Steel fiber properties:

Density $\rho_f := 7850 \frac{kg}{m^3}$

Factors $\gamma_f := 1.5$ $\gamma_{f.SLS} := 1.0$

Residual Tensile Strengths

Class-R1 $f_{R1} := 4.0MPa$

Class-R3 $f_{R3} := 3.9MPa$

Characteristic Tensile Strengths

Class-R1 $f_{ft.R1} := 0.45 \cdot f_{R1} = 1.8 \cdot MPa$

Class-R3 $f_{ft.R3} := 0.37 \cdot f_{R3} = 1.443 \cdot MPa$

e. Design tensile strength:

Ultimate Limit State:

Orientation Factor $\eta_f := 1.0$

Structural Factor $\eta_{det} := 2$

Class R1 $f_{ftd.R1} := \eta_f \cdot \eta_{det} \cdot \frac{f_{ft.R1}}{\gamma_f} = 2.4 \cdot MPa$

Class R3 $f_{ftd.R3} := \eta_f \cdot \eta_{det} \cdot \frac{f_{ft.R3}}{\gamma_f} = 1.924 \cdot MPa$

Serviceability limit state:

Class R1 $f_{ftd.R1.SLS} := \eta_f \cdot \frac{f_{ft.R1}}{\gamma_{f.SLS}} = 1.8 \cdot MPa$

Ductility Check:

$$C_1 := 100 \cdot \frac{f_{R1}}{f_{ctk0.05}} = 150.556$$

$$C_3 := 100 \cdot \frac{f_{R3}}{f_{R1}} = 97.5$$

$$Check_{C1} := \begin{vmatrix} \text{"Ok"} & \text{if } C_1 \geq 50 \\ \text{"Not Ok"} & \text{otherwise} \end{vmatrix} = \text{"Ok"}$$

$$Check_{C3} := \begin{vmatrix} \text{"Ok"} & \text{if } C_3 \geq 50 \\ \text{"Not Ok"} & \text{otherwise} \end{vmatrix} = \text{"Ok"}$$

Fiber pull strength $\sigma_f := f_{ftd.R3} = 1.924 \cdot MPa$

Tensile strain $\varepsilon_{ct} := \frac{f_{ctd}}{E_{cm}} = 4.882 \times 10^{-3} \cdot \%$

Specimen depth $l_{cs} := \lambda \cdot h = 160 \cdot mm$

Crack width $w := 2.5mm$

Ultimate fiber strain $\varepsilon_{ftu} := \varepsilon_{ct} + \frac{w}{l_{cs}} = 0.016$

Compression strain $\varepsilon_c := \frac{\varepsilon_{ftu} \cdot x}{h - x}$

$$\varepsilon_{c3} := 0.175\%$$

Compression stress $\sigma_c := f_{cd} \cdot \frac{\varepsilon_c}{\varepsilon_{c3}}$

As we know, $F_c := F_f + F_{st}$

Equation of balance

$$f_{cd} \cdot \frac{\frac{\varepsilon_{ftu} \cdot x}{h-x}}{\varepsilon_{c3}} \cdot b \cdot \frac{x}{2} = \sigma_f \cdot b \cdot (h - x) + A_s \cdot f_{yd}$$

$$x := \frac{A_s \cdot f_{yd} + b \cdot \sigma_f \cdot h}{b \cdot \sigma_f + \eta \cdot \lambda \cdot b \cdot f_{cd}} = 31.097 \cdot mm$$

$$\varepsilon_c := \frac{\varepsilon_{ftu} \cdot x}{h - x} = 0.289 \cdot \%$$

$$\sigma_c := f_{cd} \cdot \frac{\varepsilon_c}{\varepsilon_{c3}} = 42.05 \cdot MPa$$

Compression forces $F_c := \lambda \cdot x \cdot \eta \cdot f_{cd} \cdot b = 761.266 \cdot kN$

Fiber tension forces $F_f := \sigma_f \cdot b \cdot (h - x) = 389.962 \cdot kN$

Steel tension forces $F_{st} := A_s \cdot f_{yd} = 371.304 \cdot kN$

Fiber + steel tension forces $F_f + F_{st} = 761.266 \cdot kN$

a. Moment Capacity:

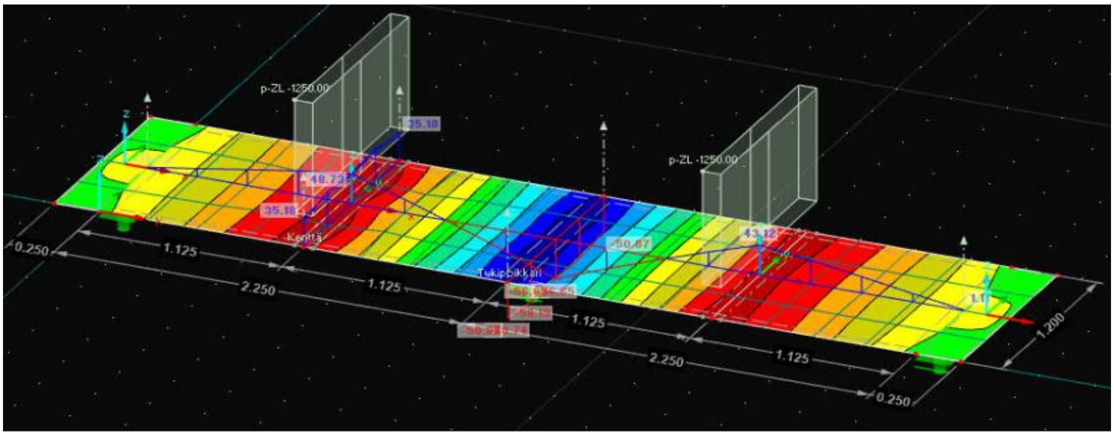
$$M_{Rd} := F_c \cdot \frac{2}{3} \cdot x + F_f \cdot \frac{h - x}{2} + F_{st} \cdot (d - x) = 100.662 \cdot kN \cdot m$$

APPENDIX C:

COVENTIONALLY REINFORCED SLAB DESIGN:

The design of conventionally reinforced slab was carried out by *Jussi Voutari*. Point load of 150kN was distributed along the width in form of a line-load. Following is the design procedure followed;

Force / Span	150kN
Load area	0.1 x 1.2 m^2
Uniform loading	1250 kN/m^2



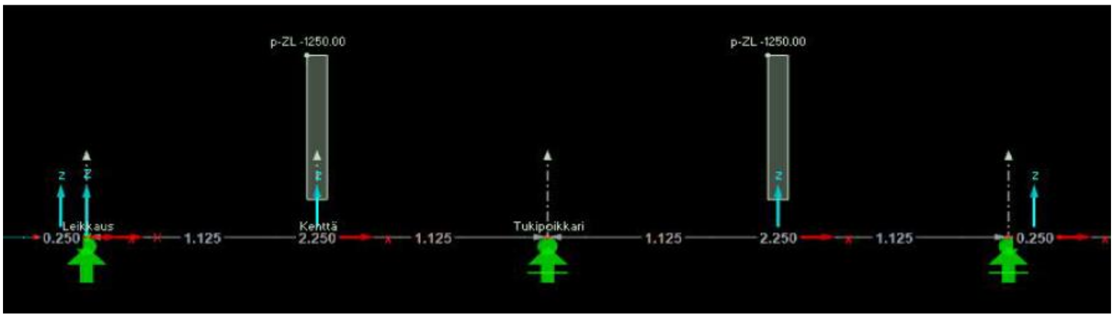


Figure 101: FEM calculations of loads on slab

The calculations were provided in the form of tables showing the reinforcement calculations and moment capacities.

Calculations are distributed and performed while taking the following design strategies in context;

- Field moment
- Support moment
- Minimum reinforcement

Table 25: Field moment and reinforcement calculations

		C35/45 onn.			
h	200mm			wk KRT_b	0,20mm
b	1200mm			wk KRT_c	0,15mm
d	166mm			c.nom	30mm
			käyttöaste		
ϕ 1	**7T8**	K 0	100 %	c (halkeilulask.)	30mm
ϕ 2	**6T8**	K 0	100 %	A_{sl} valittu	**682mm²/m**
ϕ 3	**1T6**	K 0	100 %	A_{sl} min	**333mm²/m**
			Kestävyydet	Käyttöaste	
M_{RT}			**54,98 kNm**	99 %	

Table 26: Support moment and reinforcement calculations

		C35/45 onn.			
h	200mm			wk KRT_b	0,20mm
b	1200mm			wk KRT_c	0,15mm
d	166mm			c.nom	30mm
			käyttöaste		
ϕ 1	**7T8**	K 0	100 %	c (halkeilulask.)	30mm
ϕ 2	**10T8**	K 0	100 %	A_{sl} valittu	**855mm²/m**
ϕ 3	**0**	K 0	0	A_{sl} min	**333mm²/m**
			Kestävyydet	Käyttöaste	
M_{RT}			**68,41 kNm**	99 %	

Table 27: Minimum reinforcement

C35/45 onn.					
h	200mm			wk KRT_b	0,20mm
b	1200mm			wk KRT_c	0,15mm
d	166mm			c.nom	30mm
			käyttöaste		
ϕ 1	**7T8**	K 0	100 %	c (halkeilulask.)	30mm
ϕ 2	**0**	K 0	0	A_{sl} valittu	**351mm²/m**
ϕ 3	**0**	K 0	0	A_{sl} min	**333mm²/m**
			Kestävyydet	Käyttöaste	
M_{RT}			**28,70 kNm**	0 %	

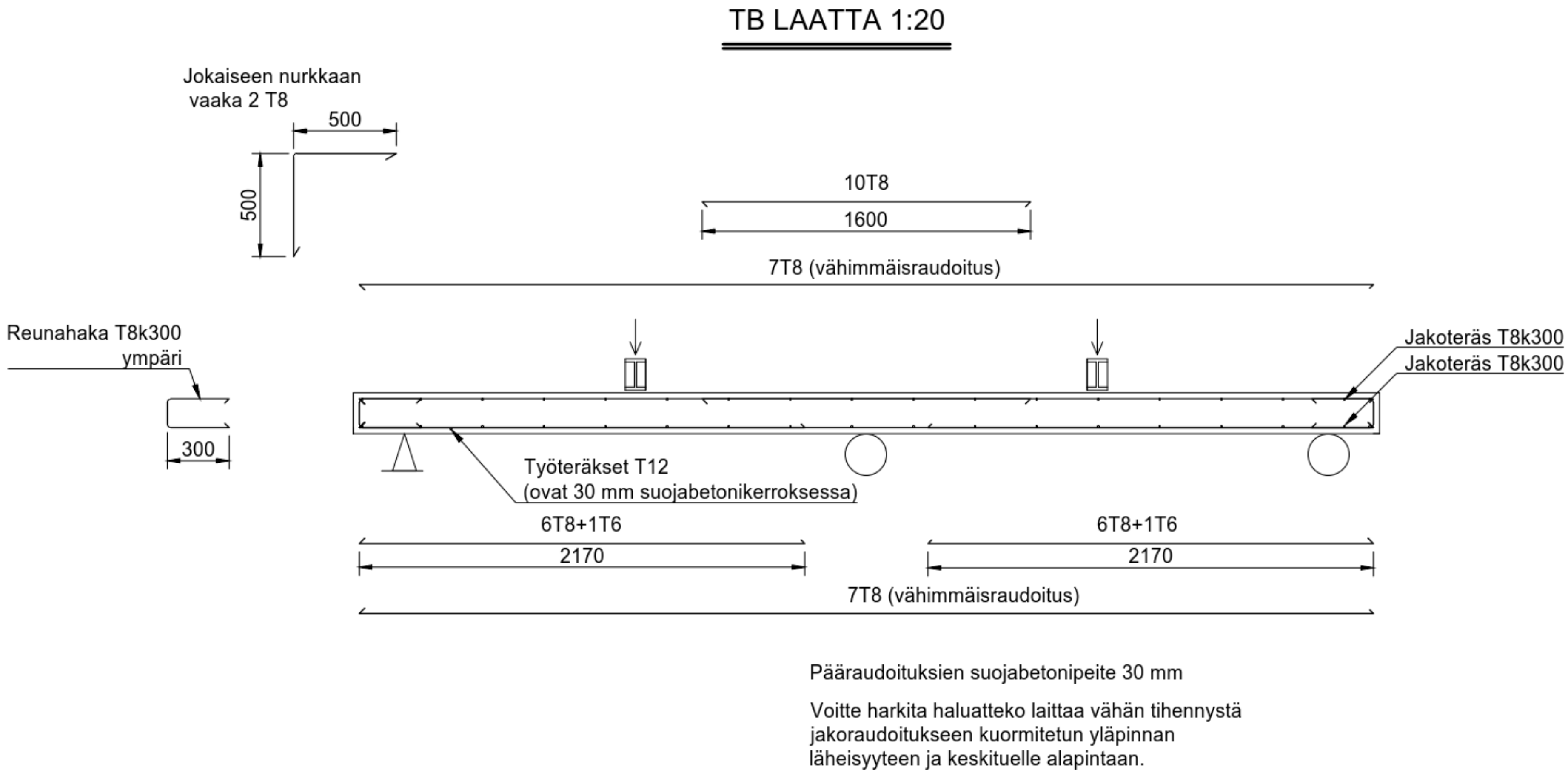


Figure 102: Conventional reinforcement pattern